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Research

Polymerized Crumb Rubber Modified Mixtures in Minnesota

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The LCMR is composed of 16 legislators, appointed by their peers to make funding recommendations to the legislature for special natural resource projects. This project was the result of such a recommendation.

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16. Abstract (Limit: 200 words)

This research program was based on laboratory and field studies. All work was limited to the use of a 10-mesh crumb rubber in the dry process. An evaluation of the asphalt-rubber interactions indicated that there should be a reasonable level of interaction between the crumb rubber and the asphalt cement selected for the project. A suggested criterion for defining an acceptable level of interaction would be to establish a minimum viscosity of 15 Poise (Brookfield viscosity) for a neat asphalt cement modified with 20 percent crumb rubber.

When designing a crumb rubber modified mixture, the aggregate gradation should be substantially gapped. The target gradation used in the construction of the Babbit, Minnesota test sections should be considered as a guideline for an acceptable gapped gradation. Stockpile gradations should be adjusted for crumb rubber gradations volumetrically; generally, 1 gram of crumb rubber occupies the same volume as 3 grams of aggregate for a given sieve size. The optimum asphalt content for CRM mixtures should be based on air voids from 1.5 to 3 percent.

During construction, the crumb rubber (supplied in 50 lbs. bags) should be added through the recycled asphalt (RAP) hopper (drum plant) or directly into the pug mill (batch plant). Laydown and compaction procedures should proceed as usual. Use of vibration on the rollers should be used at the discretion of the field engineer.

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Polymerized Crumb Rubber Modified Mixtures in Minnesota

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EXECUTIVE SUMMARY

On behalf of the Legislative Commission on Minnesota Resources and the Minnesota Department of Transportation (Mn/DOT), the University of Minnesota conducted an evaluation of both asphalt-rubber interactions and asphalt-rubber mixtures using the dry process. Experimentation with pre-treating the rubber in order to reduce its demand for key asphalt components was also investigated.

OBJECTIVES

The objectives of the research program were to:

1. Define asphalt-rubber interactions.
2. Conduct a preliminary assessment of both laboratory tests and the resulting mixture properties of crumb rubber modified bituminous (CRM) mixtures.
3. Evaluate both the fundamental properties and field performance of CRM mixtures.

SCOPE

A total of four experimental designs were developed to meet the objectives of this research program. The first two of these designs were based only on laboratory testing and covered the topics of asphalt-rubber interactions and the preliminary assessment of CRM mixture properties. The asphalt-rubber interaction study used one crumb rubber gradation with various sources of asphalt cement. Measurements of changes in the Brookfield viscosity were used to assess the interactions. The preliminary assessment of CRM mixture properties used a standard laboratory gradation and local Minneapolis, Minnesota aggregate source to evaluate the influence in mixture properties due to changes in both the percentage of crumb rubber and minor gradation changes.

The last two designs included both laboratory and field testing for pavement test sections placed in Hennepin County, and the City of Babbit, Minnesota. The Hennepin County test sections consisted of four test sections which were placed in September 1992 on CSAH 13 near

Rogers, Minnesota. The Babbit, Minnesota test sections consisted of a total of six test sections which were placed on CSAH 112 (Babbitt Road) in Babbitt, Minnesota during September 1993.

Preconstruction laboratory testing included the development of mix designs, and an evaluation of temperature susceptibility, moisture sensitivity, and low temperature behavior of the all of the mixtures. This same testing program was used to evaluate materials obtained during construction; an evaluation of permanent deformation was also added to this testing sequence.

RESULTS AND CONCLUSIONS

Asphalt-Rubber Interactions

Interactions were measured by evaluating changes in the Brookfield viscosity of asphalt-rubber mixtures. It was necessary to make modifications to the FHWA-recommended Brookfield viscosity test method so that all ranges of asphalt-rubber viscosities could be measured. Modifications included specific material handling procedures, shear rate sweeps at higher rotational speeds, and use of various size spindles.

Asphalt-rubber binders prepared with industrial tires have viscosities that are more variable than binders prepared with passenger tire rubber. The coefficient of variation for this study were 10 and 15 percent for passenger and industrial tire modified binders, respectively. Industrial tire modified binders consistently showed less of a viscosity increase than passenger tire rubber. This was possibly due to the dissolution of the industrial tire rubber rather than its swelling in asphalt cements. More fundamental work (i.e., parallel plate rheology) is needed to confirm this hypothesis. Viscosities increased with increasing concentrations of rubber, regardless of type of rubber.

The non-Newtonian, or dependency of viscosity on shear rate, behavior of asphalt-rubber binders increased with increasing concentrations of rubber. A lower viscosity neat asphalt increased the reaction of the rubber with the asphalt cement when compared to a higher viscosity asphalt from the same refinery. Each combination of asphalt and type of rubber produced a uniquely modified binder. Therefore, the compatibility of the rubber and asphalt cement should be part of the quality control testing during construction in order to identify changes in the composition of the crumb rubber. The compatibility of rubber and asphalt cements can be evaluated by measuring the viscosities of these modified binders with a Brookfield viscometer and appears to be a function of the molecular weight of the asphalt cement.

Pretreatment of rubber with tall oil pitch reduced the compatibility of the rubber and asphalt cement. The reduction in compatibility increased with increasing levels of pretreatment. A corresponding decrease in aging was seen.

Preliminary Laboratory Investigation of Mixture Properties

An optimum tall oil content of 5 percent (by weight of crumb rubber) was selected based on a modified fine aggregate absorption test. Various mixtures were then prepared with both treated and untreated crumb rubber. The preliminary assessment of the crumb rubber modified (either pre-treated or untreated) mixture properties indicated that the optimum asphalt cement content could be expected to increase as compared to typical asphalt cement contents of unmodified mixtures. All crumb rubber modified mixtures appeared to be difficult to compact (i.e., obtain a consistent, desired level of density); minor gradation changes had a significant influence on the mixture density.

Hennepin County Test Sections

These sections used crumb rubber pre-treated with tall oil pitch. Both a typical Minnesota dense gradation volumetrically-modified to hold 6 percent crumb rubber, and a gap-graded gradation with 3 percent crumb rubber were used to construct 3 test sections.

The resilient moduli for mixtures with pre-treated crumb rubber were reduced to approximately 70 percent of the unmodified gap-graded mixtures over a wide range of temperatures. This was not unexpected as the resilient modulus is a measurement of elastic rebound; as recoverable deformation is increased, the modulus decreases.

After noting problems with excessive ravelling in the test sections, the moisture sensitivity of the materials used for the mix design work was evaluated. This testing showed that moisture sensitivity increased for both mixtures with crumb rubber. These mixtures also had very low initial resilient moduli and tensile strengths, which appears to have compounded the problem with the increased moisture sensitivity.

Mix designs did a good job of estimating the air voids and stability of the gap-graded mixtures. However, the properties of the laboratory-mixed Type 41-R did not come close to matching those obtained from field mixed samples. Possible reasons for this discrepancy include 1) differences between the aggregates used for the mix design and construction, 2) sensitivity of dense-graded mixtures with crumb rubber to small gradation changes, 3) differences in methods of adding the crumb rubber in the laboratory and field, and 4) different storage times of pretreated rubber.

Further investigation after the construction of the field test sections indicated that the asphalt-tall oil pre-treated crumb rubber interactions changed with storage time. The asphalt-rubber interactions, as measured by determining the Brookfield viscosity, were substantially decreased with increasing storage time. Based upon the results of the both the laboratory testing and the field sections, this reduction in interaction also appeared to result in a reduction of the adhesive bond between the rubber and the asphalt cement. This in turn appeared to lead to excessive raveling of the crumb rubber mixture. A change in the pre-treatment to a lighter fraction petroleum-based product was suggested for the remainder of the research program.

Babbitt, Minnesota Test Sections

The pre-construction laboratory investigation of the control and crumb rubber modified mixture (either Hydrolene 90 pre-treated or untreated) properties indicated that there was little difference in the temperature susceptibility (i.e., resilient modulus versus temperature relationship) for the gradations selected. While the moisture sensitivity of the CRM mixtures increased slightly, the change was not considered to be an indication of a significant problem. The CRM mixtures indicated a possible improvement in the cold temperature properties of the mixtures, however the field sections will have to be monitored over the next several years before any firm conclusion can be drawn.

Laboratory testing of the behind the paver mixture samples produced resilient moduli similar to those obtained during the pre-construction testing program. As with the preconstruction testing, the pretreated CRM mixtures showed the greatest ability to dissipate stress through strain. However, there was little difference between the untreated CRM and control mixtures. This could indicate that the pretreated CRM mixture sections have potential for thermal cracking. The permanent deformation characteristics showed that the control mixtures had the highest stiffness, followed by the pretreated and then untreated CRM mixtures. The implications of these results on the anticipated pavement performance are unclear without long term evaluations of the test sections. Long term pavement performance evaluations will need to be conducted before any firm conclusions can be reached.

RECOMMENDATIONS

Based on the research presented in this report, an approach for the future design and construction of crumb rubber modified asphalt concrete mixtures is suggested. These recommendations are based on using a dry process for adding coarser (i.e., approximately 10 mesh) crumb rubber particles.

Evaluation of Asphalt-Rubber Interactions

There should be a reasonable level of interaction between the crumb rubber and the source/grade of asphalt cement selected for the project. A suggested criterion for defining an acceptable level of interaction would be to establish a minimum viscosity of 15 Poise at 185°C for a neat asphalt cement modified with 20 percent crumb rubber. This viscosity is measured with the Brookfield viscometer, a No. 3 spindle, and a rotational speed of 50 RPM's. The specific testing procedure is defined in Chapter Three. This level of viscosity appears to indicate that the solubility parameters of the selected asphalt cement and the crumb rubber are similar and compatible. The ability to obtain a sufficient level of interaction appears to be necessary regardless of whether the crumb rubber has been pretreated.

The percentage of crumb rubber used in any given project will vary widely and is ultimately dependent upon the method of modification selected (i.e., wet vs. dry process). The use of a constant percentage of crumb rubber allows for a uniform basis on which to evaluate asphalt-rubber interactions.

Selection of Aggregate Gradation and Optimum Asphalt Cement Content

The aggregate gradation should be gap-graded in order to provide the space necessary for the crumb rubber particles. The aggregate should be gapped towards the coarse side (i.e., below the maximum density line) for the best results. The target gradation used in the construction of the Babbitt, Minnesota test sections should be considered as a guideline for an acceptable gapped gradation. Gapping the gradation on the fine side can result in difficulty in compaction and premature pavement failures.

Stockpile gradations should be blended with crumb rubber gradations volumetrically; generally, 1 gram of crumb rubber occupies the same volume as 3 grams of aggregate for any given sieve size.

The optimum asphalt cement content for CRM mixtures should be based on air voids from 1.5 to 3 percent. This range, while lower than for unmodified mixtures, insures the mixture can be compacted easily and the higher film thickness should help the pavement durability. Other standard mix design parameters should be checked to insure that Marshall stability and the voids in mineral aggregate are within traditionally acceptable ranges.

Construction Practices

When a drum plant is used to produce the asphalt concrete mixture the crumb rubber, supplied in approximately 23-kg (50-lb) polyethylene bags, can be added through the recycled asphalt pavement (RAP) hopper. Metering control of the percent of crumb rubber added should be accomplished by emptying the required number of bags into the hopper for a given quantity of hot mix moving through the plant. The same concept should be followed for using a batch plant with the exception that the crumb rubber is added to the pug mill after the introduction of the aggregate and asphalt cement.

Laydown and compaction procedures should proceed as usual. Use of vibration on the rollers should be used at the discretion of the field engineer.

CHAPTER ONE

Today's growing tire disposal problem has motivated many public and private agencies to engage in research to find useful and cost effective long-term uses for waste tires. Minnesota agencies were further motivated when land-filling waste tires became illegal in 1985. The Intermodal Surface Transportation Efficiency Act (ISTEA), passed by Congress in 1992, provided further impetus by requiring the states to use an increasing percentage of rubber in the construction of asphalt concrete pavements over the next five years.

Crumb rubber has been added to asphalt concrete mixtures since the mid 1950's by various processes with mixed results. The most used, and better established method, uses the rubber as a polymer modification of the asphalt cement (i.e. wet process). While this process generally produces pavements that have good performance, the cost of the binder is increased anywhere from one to two times, making this process an economically difficult choice. Using the crumb rubber as an aggregate substitute (i.e. dry process) added during mixing is more appealing economically, but existing patents and unreliable results have hindered its use. There are many variations of these processes, some of which have already been tried by the Minnesota Department of Transportation (Mn/DOT). Thus far there has not been a particular process that has been able to command a large market, based on a cost-effective high performance product.

One of the most promising variations of incorporating crumb rubber into hot mix asphalt concrete has been to combine polymers and crumb rubber. These products have been used with varying degrees of success and are continuing to gain in popularity. The concept of combining the properties of crumb rubber and polymers or of polymerizing the crumb rubber without extensive modifications to plant operations has not been widely pursued.

On behalf of the Legislative Commission on Minnesota Resources and the Minnesota Department of Transportation (Mn/DOT), the University of Minnesota conducted an evaluation of both asphalt-rubber interactions and asphalt-rubber mixtures using the dry process. Experimentation with pre-treating the rubber in order to reduce its demand for key asphalt components was also investigated.

INTRODUCTION

OBJECTIVES

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2. Conduct a preliminary assessment of both laboratory tests and the resulting mixture properties of crumb rubber modified bituminous (CRM) mixtures.
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A total of four experimental designs were developed to meet the objectives of this research program. Two of these designs were based only on laboratory testing and covered the topics of asphalt-rubber interactions and the preliminary assessment of CRM mixture properties. The last two designs included both laboratory and field testing for pavement test sections placed in Hennepin County, and the City of Babbit, Minnesota.

SCOPE

Asphalt-Rubber Interactions

This experimental design used a Brookfield rotational viscometer to evaluate the effect of crumb rubber (CR) type, percentage, and level of pretreatment with two grades of asphalt cement. In addition, four asphalt cements with widely varying chemistries were obtained from the Strategic Highway Research Program (SHRP) Materials Reference Library (MRL) so that the effects of asphalt chemistry on asphalt-rubber interactions could be evaluated.

Preliminary Assessment of CRM Mixture Properties

This laboratory program evaluated the influence of changes in aggregate gradation, percent of CR, and use of pretreatment on mix design results, as well as temperature susceptibility and low temperature behavior.

Field Test Sections

Hennepin County Test Sections

Four test sections were placed in September, 1992 on CSAH 13 near Rogers, Minnesota. The test sections consisted of a control section of the typical Hennepin county Type 2341 mix, the Type 2341 mix modified with 6 percent crumb rubber pretreated with 5 percent tall oil, and a gap-graded crushed granite mixture without and with 3 percent pretreated crumb rubber. The mix design parameters were determined and the temperature susceptibility of both laboratory and field mixed materials were evaluated. Additionally, the moisture sensitivity for laboratory mixed materials, and influence of methods of adding crumb rubber during laboratory mixing were evaluated.

Babbit, Minnesota Test Sections

A total of six test sections were placed on CSAH 112 (Babbitt Road) in Babbitt, Minnesota during September, 1993. There were two control, dense graded test sections (one at either end of the project), two test sections with either 1 percent untreated or pretreated rubber in the top 50 mm (2 in) wear course, and two test sections with either 1 percent untreated or pretreated rubber in the base, binder, and wear courses (total 150 mm (6 in)) of CRM mixtures.

Preconstruction laboratory testing included the development of mix designs, and an evaluation of temperature susceptibility, moisture sensitivity, and low temperature behavior of the all of the mixtures. This same testing program was used to evaluate materials obtained during construction; an evaluation of permanent deformation was also added to this testing sequence.

CHAPTER TWO

GENERAL

Even though the history of the usage of the asphalt-rubber mixture spans more than 30 years, a standard specification is not available in the United States. A specification is needed to guide an agency through the design and construction process by indicating the types of materials and methods of fabrication required to produce the desired results. Asphalt-rubber specifications are not different in this respect and consequently begin with definitions essential to understanding the specialized terminology of asphalt-rubber technology.

Asphalt concrete is a mixture of asphalt cement and aggregate with or without any other material. In other words, any paving mixture whose components are at least asphalt cement and aggregate will be called an asphalt concrete.

Crumb rubber modifier (CRM) is a general term for scrap tire rubber that is reduced in size and is used as a modifier in asphalt paving material (1).

Asphalt-rubber binder is a mixture of asphalt cement, reclaimed (recycled) tire rubber, which may contain some additives in the *wet method*. The wet method is any method that blends CRM with the asphalt cement prior to incorporating the binder in the asphalt paving mix. Sometimes it is used as a liquid binder and added to the hot aggregates in order to produce a *CRM asphalt concrete*.

CRM asphalt concrete is a mixture of asphalt cement, reclaimed (recycled) tire rubber, aggregates, which may contain some additives in either the wet process or the *dry method* (1). In the wet process, the asphalt-rubber binder is used in the production of hot mix asphalt concrete. In the dry process, the CRM is considered primarily as a rubber aggregate; this product is defined as a *rubber modified hot mix asphalt (RUMAC)*.

An *asphalt-rubber mixture* is a blend of asphalt cement and reclaimed (recycled) rubber with or without any other material. In other words, any paving mixture whose components are at least asphalt cement and reclaimed (recycled) rubber, e.g., asphalt-rubber binder and CRM asphalt concrete, is defined as an asphalt- rubber mixture.

LITERATURE REVIEW

CRM PROCESS

There are several ways of producing CRM material depending on the desired end product mesh size and configuration. The most common ways are (1):

Ambient grinding	6.4 mm (1/4 in) to 0.43 mm (# 40 mesh)
Ambient granulating	6.4 mm (1/4 in) to 0.43 mm (# 40 mesh)
Cryogenic Grinding	6.4 mm (1/4 in) to 0.15 mm (# 100 mesh)
Wet Grinding	0.43 mm (# 40 mesh) to 0.15 mm (# 100 mesh)

Each of these processes has its advantages and disadvantages in terms of economics and particle size distributions.

Ambient Grinding and Granulating

The ambient grinding/granulating process is usually accomplished by cracker mills or granulators (1). All size reduction takes place at room temperature. The actual particle reduction is accomplished by a tearing or shearing action. This creates a particle with a rough surface, perhaps described as spongy. This process is very efficient for the production of the coarser mesh products and usually results in the lowest cost for coarser than 50 mesh materials.

The ambient process consists of cracker mills or granulators, screeners, conveyors and various types of magnets to remove any steel wire or other steel particles if the material starts out as whole tire chunks. A fabric removal system is also required. In addition, there may also be stone removal equipment in the overall system.

Cryogenic Grinding

In this process the rubber is frozen by the use of liquid nitrogen. This causes the rubber to become very brittle and it, in turn, is easily fractured in a hammer mill. Reportedly the surface is very "clean faceted" and, thus, has much less surface area than ambiently ground material (1). This process consists of a pre-cooler to chill the material, a grinder, appropriate screen and conveyors and steel and fiber separation systems.

Wet Grinding

In this process a coarse CRM is placed in a wet slurry and is ground between grinding stones, producing a particle that may be similar to an ambient ground material. Before the material is processed in the wet grinding system it must be reduced in size using another process as stated above, typically ambient grinding. The wet grind process requires a very effective drying system which is not required for the other two processes, ambient and cryogenic (1).

ASPHALT-RUBBER BINDER

An asphalt-rubber binder is a mixture which serves as the binder in a dense, open or gap graded asphalt-rubber concrete. The rubber component is at least 15 percent by weight of total binder, and it is fully dispersed in the asphalt cement (wet method). This new binder can be used in the same way as conventional asphalt cement to produce a CRM asphalt concrete. Where this binder is sprayed onto the surface and followed by distribution and rolling of a cover aggregate, the material is referred to as a *seal coat*, *chip seal* or *stress absorbing membrane (SAM)*, depending on its purpose. When such a treatment is placed between the layers of a pavement system to retard reflection cracking, it is referred to as a *stress absorbing membrane interlayer (SAMI)*.

Two procedures for making the asphalt-rubber binder are available depending on whether the rubber is vulcanized (no treatment by heat, pressure, or the addition of softening agents to alter the chemical composition of the material) or devulcanized (treatment by heat, pressure, or the addition of softening agents to alter the chemical composition of the material). The main differences between the two methods are the proportions of asphalt and rubber, the introduction of viscosity-reducing agents, the mixing time, and the mixing temperature (2, 3).

Asphalt-Rubber Binder Using Vulcanized Rubber

Ambiently or cryogenically ground rubber with a specific gravity of 1.15 ± 0.03 is used. The rubber is free of loose fabric, wire, and other contaminants except up to 4 percent (by weight of rubber) calcium carbonate may be included to prevent rubber particles from sticking together. Three gradations (Type I, Type II, and Type III) have been suggested (Table 2.1), however, these may change based on the type of rubber and/or usage (2).

The proportions of asphalt cement and rubber are 78 ± 1 percent asphalt cement and 22 ± 1 percent rubber by weight of asphalt-rubber mixture. The materials are combined as rapidly as possible for a time and a temperature such that the consistency of the material is homogeneous. The temperature of the asphalt cement is between 177 and 232°C (350 and 450 °F). The necessary reaction time required to achieve homogeneity varies from about 10 minutes at 232°C (450°F) to up to as much as one hour at 177°C (350°F). Kerosene may be added to improve spraying and wetting viscosity in amounts up to 7.5 percent, by volume, of the hot asphalt-rubber mixture. It is emphasized that suitable fire precautions be exercised if kerosene is used (2)

Table 2.1. Gradation of Particulate Tire Rubber for Use in Asphalt-Rubber (3).

Sieve	Percent Passing			
Size (mm)	Type I	Type II	Type III	Type IV
2.36 (# 8)	100	100		
2.00 (# 10)	95-100	95-100		
1.18 (# 16)		70-80	100	
0.85 (# 20)			95-100	
0.60 (# 30)	0-10	5-15	60-80	60-80
0.43 (# 40)	0-5	0-5		
0.30 (# 50)			0-10	15-40
0.15 (# 100)				0-15

Asphalt-Rubber Binder Using Devulcanized Rubber

A free flowing blend of 40 percent devulcanized and 60 percent vulcanized rubber consisting of truck and bus tread rubber is used. The specific gravity of the rubber is 1.15 ± 0.03. The rubber is free of loose fabric, wire, and other contaminants except up to four percent (by weight of rubber) calcium carbonate may be included to prevent rubber particles from sticking together. The gradation (Type IV) is shown in Table 3.1 (2).

Asphalt cement is heated at 121 to 204°C (250 to 400°F) and combined with from 2 to 6 percent (by weight of asphalt cement) of an added extender oil (kerosene-type diluent) to reduce viscosity to the range of 600 to 1800 poises at 60°C (140°F) when tested in accordance with ASTM D2171. The mixture is thoroughly mixed by recirculation, stirring, air agitation, or other means. The proportions of asphalt cement and rubber are 78 ± 1 percent asphalt cement and extender oil and 22 ± 1 percent rubber. The temperature of the asphalt cement and extender oil is increased to the range of 177 to 218°C (350 to 425°F) and the rubber is added as rapidly as possible and recirculated for a period of not less than 30 minutes after incorporation of all the rubber. The asphalt-rubber temperature is maintained at 177 to 218°C (350 to 425°F) during the recirculation period (2).

APPLICATION OF ASPHALT-RUBBER BINDER IN PAVEMENTS

There are several ways to use the asphalt-rubber for the paving materials. The most common applications are (1):

1. Sealants for Crack and Joint
2. Stress Absorbing Membrane (SAM)
3. Stress Absorbing Membrane Interlayer (SAMI)
4. Subgrade Seals

Sealants for Crack and Joint

Asphalt-rubber binder is commonly used as a sealant for cracks and joints in pavements across the United States. To choose a sealant for a given location, some consideration should be given to the type of pavement, type of crack, traffic, and environmental conditions.

Stress Absorbing Membrane (SAM)

A surface treatment using asphalt-rubber binder followed by cover aggregate is called a stress absorbing membrane. The asphalt-rubber binder and cover aggregates should be evaluated to design a SAM. The amount of crumb rubber is typically 20 to 30 percent by weight of asphalt cement. Cover aggregate is generally a uniform 9.5 to 6.4 mm (3/8 to 1/4 in) sieve size and preferably hot precoated with 0.3 - 0.5 percent asphalt cement by weight. The engineering properties of a SAM can resist and delay the development of reflective cracks when the cracks are generally inactive such as closely spaced random or block cracking. A SAM, however, cannot resist the amount of strain that is typical of major transverse thermal crack in asphalt concrete pavements (4).

Composite Designs - Stress Absorbing Membrane Interlayer (SAMI)

The principal concept of the composite design with SAMI is to place a membrane beneath the overlay which can resist the stress of reflective cracks, delay the propagation of the crack, and prevent moisture penetration through the new overlay.

Two composite designs with SAMI's are available, a two-layer SAMI and a three-layer SAMI (4). A two-layer SAMI places the SAMI on the existing pavement and overlays the SAMI with 2.54 to 7.62 cm (1 to 3 in) of hot mixed asphalt-rubber concrete. A three-layer SAMI begins with the placement of a leveling course of hot mixed asphalt-rubber concrete. This initial overlay provides an acceptable uniform surface for placing the SAMI. The SAMI is followed by an additional 2.54 to 7.62 cm (1 to 3 in) of hot mixed asphalt-rubber concrete overlay. This system applies when there is deterioration of the existing pavement cracks and joints. If a two-layer SAMI is used, the deteriorated cracks would create a discontinuity in the membrane at the location where the membrane will be subjected to the highest levels of stress and the performance of the SAMI would be diminished.

Subgrade Seals

This is a spray application of asphalt-rubber binder similar to a SAM. It could be used to keep moisture out of a subgrade or to provide an impermeable liner for a water retention basin.

CRM ASPHALT CONCRETE

CRM asphalt concrete is composed of asphalt cement, reclaimed (recycled) tire rubber, aggregates and any other additives. It is a HMA mixture in which the asphalt-rubber binder is used in lieu of a conventional asphalt cement. It can be either an open-graded, gap-graded, or dense-graded HMA. Two categories of asphalt-rubber concrete mixing methods are available; the *wet method* and the *dry method.* The wet method is more expensive than the dry method due to the additional costs involved in pre-blending the asphalt-rubber binder as discussed previously.

Wet Method

In the wet method the asphalt cement and crumb rubber are pre-blended and are added to the hot aggregate as an asphalt-rubber binder. The crumb rubber is blended with asphalt cement for a sufficient time to achieve a uniform binder with a fairly stable consistency. The blending time can be reduced by using finer rubber, softer asphalt cement, and higher blending temperature (5). There are two technologies in this method depending on the gradation of CRM and the manner in which the CRM and the asphalt cement are blended and reacted: *McDonald technology* and the *continuous blending technology.*

McDonald Technology

In the McDonald technology, typically 15 to 22 percent ground rubber (1.18 mm (No. 16) to 0.6 mm (No. 30), Table 2.2) is mixed with an asphalt cement (usually an AC-10 or AC-20) and reacted for one-half hour to one hour (1). The aggregate gradations of an open-graded HMA mixtures are shown in Table 2.3.

Table 2.2. Suggested Rubber Gradations for McDonald Technology (1).

	Percent	Passing
Sieve Size (mm)	Dense-Graded	Open-Graded
2.00 (# 10)	100	100
1.18 (# 16)	98-100	75-100
0.60 (# 30)	70-85	25-60
0.30 (#50)	10-40	0-20
0.075 (# 200)	0-5	0-5

Table 2.3. Suggested Aggregate Gradations for Open-Graded CRM HMA Mixture (1).

	Percent	Passing
Sieve Size (mm)	Type I	Type II
19.00 (3/4 in)	100	100
12.50 (1/2 in)	100	90-100
9.5 (3/8 in)	85-100	75-95
4.75 (#4)	25-55	20-45
2.36 (#8)	5-15	5-15
0.60 (#30)	0-10	0-10
0.075 (# 200)	0-5	0-5

Continuous Blending Technology

In the continuous blending technology, 5 to 20 percent ground rubber is blended with AC-5 or AC-10 asphalt cement (1). The use of the fine rubber gradation reduces the reaction time between CRM and asphalt cement. Table 2.4 presents a typical gradation of the CRM used in this technology.

Table 2.4. CRM Gradation for Continuous Blending Technology (1).

Sieve Size	Percent Passing
0.25 mm (# 60)	98-100
0.18 mm (# 80)	88-100
0.15 mm (# 100)	75-100

Dry Method

In the dry method, generally, crumb rubber is added to either the hot aggregate as a non-mineral filler, or after the aggregate and asphalt cement have been mixed (i.e., pug mill mixing). This method was originally developed in Sweden during the 1960's and patented under the trade names of "Rubit" in Sweden and "PlusRide" in the United States. There are two technologies in the dry method depending on the CRM and aggregate gradations: *PlusRide technology* and the *generic dry technology*.

PlusRide Technology

The PlusRide technology modifies a conventional gap-graded aggregate gradation with the elastic properties of the reclaimed tire rubber. It is necessary to create a gap in the aggregate gradation curve to provide space for the rubber particles, especially in the 3.2 to 6.4 mm (1/8 to 1/4 in) size range. The asphalt content is generally higher than that for a conventional mixture. Unlike conventional mix design methods, the only mix design criterion is an air void content in the range of 2 to 4 percent. On the basis of experience in Alaska and Sweden, three different aggregate gradations have been recommended for different layer thicknesses to serve different traffic levels (Table 2.5). The gradation specifications for rubber are given in Table

2.6.

Table 2.5. Recommended Specifications for Rubber-Asphalt Mixture for Different Levels of Traffic for PlusRide Technology (6).

	Mix Type		
	A	B	C
Average Daily Traffic	2500	2500-10000	10000
Minimum Thickness (mm)	25	40	45
Sieve Size	% passing		
19.0 mm (3/4 in)			100
15.9 mm (5/8 in)		100	
9.5 mm (3/8 in)	100	60-80	50-62
6.4 mm (1/4 in)	60-80	30-44	30-44
2.0 mm (# 10)	23-38	19-32	19-32
0.6 mm (# 30)	15-27	13-25	12-23
0.075 mm (# 200)	8-12	8-12	7-11
6.4 mm to 2.0 mm fraction		12 max	12 max
Mix Design			
Rubber (% of Total Mix by)			
Weight	3.0	3.0	3.0
Volume	6.7	6.7	6.7
Asphalt (% of Total Mix by)			
Weight	8-9.5	7.5-9.0	7.5-9.0
Maximum Voids (%)	2.0	2.0	2.0

Table 2.6. Particle Size Specification for Rubber for PlusRide Technology (6).

	% Passing		
Sieve Size	Coarse	Fine	80/20 Blend[1]
6.35 mm (1/4 in)	100		100
4.75 mm (# 4)	70-90		76-92
2.00 mm (# 10)	10-20	100	28-36
1.18 mm (# 20)	0-5	50-100	10-24

[1] 80% coarse and 20% fine rubber in combination

Generic Dry Technology

The generic dry technology uses an equivalent or slightly lower percentage of CRM compared to PlusRide. The CRM is also finer than that used in PlusRide. A conventional dense-graded aggregate is used with only slight modification. The gradation of CRM is adjusted to suit the aggregate gradation. The CRM passing the No. 20 sieve reacts with the asphalt cement producing a modified binder. The coarse CRM replaces a portion of the aggregate in the HMA mixture, and acts as an elastic aggregate. This technology has been successfully used in New York (7) and other states. The CRM and aggregate gradations for New York project are shown in Tables 2.7 and 2.8, respectively.

Table 2.7. CRM Gradation for Generic Dry Technology (7).

	Percent	Passing
Sieve Size	Specified	Supplied
6.40 mm (1/4 in)	100	-
4.75 mm (# 4)	-	100
3.20 mm (1/8 in)	75-85	-
2.00 mm (# 10)	45-55	51
0.85 mm (# 20)	30-40	44
0.425 mm (# 40)	0-10	19

Table 2.8. Aggregate Gradation for Generic Dry Technology (7).

Sieve Size	Percent Passing	Tolerance
25.4 mm (1 in)	100	-
12.7 mm (1/2 in)	95-100	-
6.35 mm (1/4 in)	65-85	± 7
3.165 mm (1/8 in)	36-65	± 7
0.85 mm (# 20)	15-39	± 7
0.425 mm (# 40)	8-27	± 7
0.180 mm (# 80)	4-16	± 4
0.075 mm (# 200)	2-6	± 2

ADVANTAGES/DISADVANTAGES OF USING CRUMB RUBBER IN PAVEMENTS

Some anticipated benefits of adding crumb rubber to the asphalt concrete pavement, in a pavement engineers view, are increased flexibility, skid resistance, fatigue life, as well as reduced crack reflection control, traffic noise, and aging (6, 8, 9). The increased flexibility and skid resistance are expected because of the rubber particles in the asphalt-rubber mixture. Since the elastic response of asphalt-rubber mixture may be increased because the rubber is an elastic material, the flexibility of mixture may be increased. Also, since the friction of rubber is generally greater than conventional asphalt concrete mixture the CRM asphalt concrete with more rubber content has more friction. In other words, the surface of a CRM asphalt concrete pavement would be expected to have more skid resistance than that of conventional asphalt concrete pavement.

However, to evaluate the pavement performance, fatigue resistance, rutting resistance, thermal cracking resistance, and temperature susceptibility, either field observations or laboratory test, or both, should take place. Evaluation of these benefits of asphalt-rubber mixtures (asphalt-rubber binder and asphalt-rubber concrete) are reviewed from literature in this section and summarized in Table 2.15.

University of Toronto Study

The University of Toronto conducted several tests to determine the extent of the interaction between asphalt cement and reclaimed rubber from used tires; the void content and Marshall stability and flow of a CRM asphalt concrete mixture were evaluated (10). In addition to laboratory testing, pavement test sections were also constructed with these materials to evaluate the field performance.

The viscosity of the asphalt-rubber binder was measured using the rotating cylinder method (Haake viscometer). Two types of asphalt-rubber binder (vulcanized and devulcanized) were tested. Three rubber contents (10, 20, and 30 percent) were used with an 85/100 penetration asphalt cement. The maximum size of the vulcanized rubber was 0.6 mm (No. 30) and for the devulcanized rubber it was 1.0 mm (approximately No. 20). The viscosity, measured at 110-120°C (230-248°F) at 10 min mixing time with 20 percent vulcanized rubber content was approximately 550 poises. However, that of the devulcanized asphalt-rubber binder was 170 poises. Very little interaction between the rubber and asphalt cement was observed at 200 °C (392°F), whether the rubber was vulcanized or not.

Only the vulcanized asphalt-rubber binder (20 percent rubber content) was used for Marshall tests. The presence of rubber in the hot mix asphalt-rubber concrete increased the void content and reduced the Marshall stability. The Marshall stability and void content for the conventional sample (sand to screen ratio of 3 with 6 percent asphalt content) were 750 kg (1650 lb) and 1.8 percent, respectively. Those of CRM asphalt concrete at same condition were 250 kg (550 lb) and 3.8 percent, respectively.

CRM asphalt concrete test strips, placed on a well-used plant road, withstood heavy traffic without any sign of distress, despite their low stabilities, and showed every indication of giving the expected improvement in durability.

Alaska DOT Study

Seven experimental asphalt-rubber concrete pavement sections were constructed between 1979 and 1981 by the Alaska DOT (8). In these projects, 3 to 4 percent, by weight of total mixture, of crumb rubber particles were incorporated into hot mixed asphalt concrete pavements by using the PlusRide technology. Mix design experience by the Marshall method had demonstrated that the rubber greatly changed the mix properties (reduced the Marshall stability and increased the void content), and from 1 to 2 percent more asphalt cement was normally required to the attain a 3 percent or lower void content, the primary factor used in the selection of a suitable mix design.

The asphalt-rubber paving mixture had been successfully prepared in both batch and drum-dryer plants and placed with conventional pavers and rollers. The field void content level of less than 8 percent, though high in asphalt content and compactive effort, had been shown by field experience to be critical to pavement resistance to ravelling. Field voids of less than 5 percent were highly desirable. In spite of the high asphalt contents and soft asphalt grades used in these mixes, no asphalt bleeding had occurred.

Benefits of CRM asphalt concrete pavements included the ability to shed an ice cover more quickly than conventional pavements, the development of a more flexible and fatigue-resistant pavement, and a significant reduction in tire noise. Under Alaskan conditions of icy, non-salted roadways, stopping distances averaged 25 percent less than on normal pavements.

Kuwait Study

Some rheological and stability tests were carried out to evaluate an asphalt-rubber binder in Kuwait (11). Viscosity-temperature-shear rate tests with a Haake rotational viscometer at temperatures of 60, 80, 100, 135, and 150°C (140, 176, 212, 275, and 302°F); penetration at temperatures of 5, 10, 25, 35, and 45°C (41, 50, 77, 95, and 113°F); softening point tests; toughness tests at a temperature of 25°C (77°F); tension relaxation tests at a temperature of 25°C (77°F), and Marshall stability tests were included. A Kuwait 60/70 air blown asphalt cement, two types of rubber (truck tires and automobile tires) with a maximum size was 0.6 mm

(No. 30), and a dense aggregate gradation were used. The rubber contents were between 7.5 and 30 percent by total weight of binder. The test results are shown in Table 2.9.

It was reported that the addition of reclaimed tire rubber to asphalt cement resulted in a binder exhibiting superior rheological properties suited for high temperatures. The asphalt-rubber binder showed a marked increased the viscosity and elasticity.The addition of rubber to the binder increased the softening point, toughness, stability, and hardening resistance, but reduced the ductility. The temperature sensitivity (slope of logarithm of penetration versus temperature; 1.3 for 7.5 percent rubber binder and 2 for 30 percent rubber binder) also reduced with the rubber contents. In other words, the properties of the asphalt-rubber binder could be related to phenomenological changes in pavement performance such as increased strength, durability, rutting resistance, fracture resistance, and bleeding resistance, and reduced age harding, particularly at high temperature between 40 and 60°C (104 and 140°F). An asphalt-rubber concrete pavement would be more flexible at low temperature and more rigid and elastic than the conventional asphalt concrete pavement at high temperature.

Table 2.9. Summary of Kuwait Study.

Properties	Control Binder	Asphalt-Rubber Binder
Viscosity at 100°C	6 Pa-sec	300 Pa-sec
Elasticity	3% unrelaxed load	35% unrelaxed load
Softening Point	55°C	85°C
Toughness at 300% elongation	50 g	700 g
Stability	1350 kg	1800 kg
Hardening Resistance at 1 hour mixing time	4 mm penetration	2 mm penetration
Ductility at maximum elongation	25 cm	13 cm

California DOT Study

The California Department of Transportation investigated the field performance of CRM asphalt concrete pavements in 1983 (12). Included were dense-graded asphalt concrete overlays with asphalt-rubber binder, PlusRide dense-graded CRM asphalt concrete overlays, and conventional dense-graded asphalt concrete overlays. The asphalt-rubber binders contained 78 percent AR-4000 grade asphalt, 18 percent ground reclaimed rubber, and 4 percent extender oil, by weight of total binder. The reclaimed rubber contained of 20 percent devulcanized rubber and 80 percent vulcanized rubber.

Distress began to develop in the conventional dense-graded asphalt concrete pavement within in one year in the form of raveling, rutting, and cracking. These distresses became more extensive over subsequent years. Some distresses had also developed in both CRM asphalt concrete pavements. However, all the CRM asphalt concrete pavements were performing equal to or better than equivalent or greater thicknesses of conventional dense-graded asphalt concrete pavements.

Mt. St. Helens (Washington State) Study

CRM asphalt concrete pavement overlay and a conventional asphalt concrete pavement were constructed at Mt. St. Helens in Washington in August 1983 (9). The CRM asphalt concrete used rubber and asphalt contents of 3 percent and 7.8 percent (dry method), respectively. The asphalt content of conventional asphalt concrete was 5.5 percent. Coring took place in October 1993, November 1984, and May 1986 for both mixtures to conduct laboratory evaluation with diametral resilient modulus, diametral fatigue, Hveem stabilometer, and indirect tension tests. The results are shown in Table 2.10.

Laboratory results indicated that the resilient modulus of the control mix was greater than that of CRM asphalt concrete but the fatigue life of the CRM asphalt concrete would exceed that of the control for any given strain level. The stability of control mix was greater than that of CRM asphalt concrete.

Even though Hveem stability values of CRM asphalt concrete were unacceptable based upon Asphalt Institute criteria for asphalt concrete mixture there was no evidence of rutting in field survey. Field surveys showed that both pavements to be performing well and in good condition.

Table 2.10. Summary of Mt. St. Helens Study.

Properties	Control Mixture	CRM Asphalt Concrete
Resilient Modulus (t=month)	2390 $t^{0.169}$	1585 $t^{0.215}$
Fatigue Life (for May 1986, ϵ_t=tensile strain)	$2.21 x 10^{-7} \epsilon_t^{-2.67}$	$6.23 x 10^{-14} \epsilon_t^{-4.48}$
Tensile Strength	930 kPa	740 kPa
Stabilometer	21	2

Oregon State University Study

Takallou and Hicks (6) investigated the mix design and construction guidelines for CRM asphalt concrete pavements. In this study, the PlusRide CRM asphalt concrete pavement specifications (Table 2.5) were employed for asphalt content, rubber content, aggregate gradation, and rubber gradation. The results of study are shown in Table 2.11.

The laboratory study indicated that the rubber gradation, rubber content, and aggregate gradation have a considerable effect on mix design asphalt content, fatigue life, rutting resistance, and modulus value. The study showed that the CRM asphalt concrete had better fatigue resistance but lower creep resistance. The field survey indicated that most CRM asphalt concrete pavements had not failed in fatigue.

Table 2.11. Summary of Oregon State University Study.

Properties	Control Mix	CRM Asphalt Concrete
Asphalt Content	5.5 %	7.0-9.3 %
Fatigue Life at - 6°C	15500	41000-127500
Permanent Strain (after 1 hour loading at 40°C)	7×10^{-5}	13×10^{-5}
Modulus at - 6°C	21 MPa	9.8-18.2 MPa

Virginia DOT Study

The Virginia DOT investigated the behavior of CRM asphalt concrete with laboratory tests (Marshall, creep, resilient modulus, and indirect tensile tests) in 1990 (13). An AC 30 with 6 percent extender oil and 17 percent crumb rubber by weight of asphalt cement were used for the asphalt-rubber binder. The tests results are shown in Table 2.12.

Results of Marshall test indicated that the stability of the control mixture is greater than that of CRM asphalt concrete. The VMA of both mixtures were greater than the minimum design criteria (15 percent). The resilient modulus of the control mixture was greater than the CRM asphalt concrete at a 95 percent confidence level. It was expected that the addition of crumb rubber would increase the modulus and decrease the unrecovered strain; however, both the modulus and unrecovered strain of the CRM asphalt concrete were lower than the same properties of the control mixtures. This indicated that the CRM asphalt concrete may be less resistant to permanent deformation than conventional asphalt concrete. The indirect tensile strengths of the CRM asphalt concrete were significantly lower than the control mixtures at a 95 percent confidence level.

Table 2.12. Summary of Virginia DOT Study.

Properties	Control Mix	CRM Asphalt Concrete
Stability	1380 kg	1190 kg
VMA	17.9 %	18.3 %
Resilient Modulus at 40°C	550 MPa	470 MPa
Permanent Strain at 40°C	0.0008	0.002
Tensile Strength at 40°C	760 kPa	415 kPa

Florida DOT Study

In 1988, the Florida DOT began a concentrated effort to evaluate the potential uses for reclaimed tire rubber in asphalt concrete pavements (5). The Florida DOT identified that the most advantageous use of rubber would be as a binder modifier to improve the performance of asphalt concrete pavement.

The optimum rubber content for open-graded friction course mixtures was determined to be 15 percent by weight of asphalt cement using a 0.43 mm (# 40) sieve ground tire rubber. In an open-graded mixture, the rubber allowed a significant increase in the total binder content and therefore an increased film thickness was expected to slow oxidation of binder and improve the durability of these mixtures. The optimum rubber content for dense-graded friction course mixtures had been identified as 5 percent by weight of asphalt cement using a 0.18 mm (# 80) sieve ground tire rubber. It was believed that the crumb rubber would provide improve elasticity to the binder and therefore greater resilience for these mixtures in the recovery of repeated strains due to the repeated traffic loads (the deformation resistance would be increased). All of the test sections were performing well.

Saudi Arabia Study

The effects of reclaimed rubber particles in asphalt concrete mixture were evaluated in the laboratory in Saudi Arabia (14). The rubber contents for asphalt-rubber binder were 10, 20, and 30 percent by weight of total binder and a 60/70 penetration grade asphalt cement was used. Binder tests included softening point test and viscosity test, while tests on the CRM asphalt concrete included Marshall and Hveem stability tests, split tensile strength test, creep test, resilient modulus test, and fatigue test. The test results are shown in Table 2.13.

The results shown that the softening point and viscosity in asphalt-rubber binder increased with rubber content. For CRM asphalt concrete, the Marshall stability, Hveem stability, tensile strength, resilient modulus, and fatigue life have improved with 10 percent rubber binder, however, increasing the rubber content to 30 percent resulted in a drop of them below those of control mixture.

Table 2.13. Summary of Saudi Arabia Study.

Properties	Control Binder	0 % Asphalt-Rubber Binder	10 % Asphalt-Rubber Binder
Softening Point	51°C	59°C	62°C
Viscosity at 25°C	16 kPa-sec	22 kPa-sec	23 kPa-sec
Resilient Modulus at 25°C	6640 MPa	7600 MPa	3960 MPa
Tensile Strength at 25°C	1393 kPa	1427 kPa	1100 kPa
Marshall Stability at 25°C	2750 kg	2850 kg	2000 kg
Hveem Stability at 25°C	67 kN	69 kN	64.5 kN
Fatigue Life	25000	40000	18000

The results of the static creep tests indicated that the strain recovery was improved with the rubber content (15 percent for control binder, 20 percent for 20 percent rubber binder, and 25 percent for 30 percent rubber binder).

University of Nevada Study

In order to investigate the low temperature cracking of CRM asphalt concrete a set of laboratory tests were conducted in University of Nevada (15). Three types of asphalt-rubber binders with AC 5 and AC 20 asphalt cements and ambient ground rubber (AC 5 + 17 percent rubber; AC 5 + 16 percent rubber + 5 percent extender oil; AC 20 + 16 percent rubber). The asphalt contents varied between 7.9 to 8.5 percent by total weight of mixture. The test results are shown in Table 2.14.

Table 2.14. Summary of Indirect tensile Test in University of Nevada.

Temperature	AC5	AC20	AC5RE	AC5R	AC20R
-29°C	1840 kPa	1910 kPa	1560 kPa	1745 kPa	2235 kPa
-18°C	1615 kPa	2790 kPa	1030 kPa	1220 kPa	3310 kPa
1 °C	1151 kPa	1770 kPa	340 kPa	380 kPa	890 kPa

Results of this study indicated that the fracture temperature of CRM asphalt concrete mixture with AC 5 asphalt cement was approximately 10 °C (18 °F) lower than that of the control mixture which used same grade of asphalt binder.

The indirect tensile strengths of CRM asphalt concrete with AC 20 asphalt cement were significantly greater that those of the control mixture. For AC 5 binder, however, the indirect tensile strength of CRM asphalt concrete was less than that of control mixture at any test temperature. The indirect strengths of CRM asphalt concrete with extender oil were similar with those of CRM asphalt concrete without extender oil.

Minnesota DOT Studies

The Minnesota DOT has placed several CRM asphalt concrete test sections over the last ten years. In 1984, the wet process was used to construct four test sections in TH 7, west of the Twin Cities. Two sections were also constructed in 1984 using the dry process (TH 61 near Forest Lake, and I-94 near Collegeville). The dry process was also used to construct two sections of the Willard Munger Recreational Trail in the late 1980's.

TH 7, West of Twin Cities: The Minnesota DOT evaluated the performance of an asphalt-rubber binder used in a dense graded asphalt concrete (16). The amount of rubber in the asphalt-rubber binder was 20.2 percent and AC 120/150 was used. The maximum size of the crumb rubber was 2.36 mm (No. 8 sieve).

While the resilient modulus and the air void were determined in the laboratory, the roughness and the depth of rutting were monitored in the field. Laboratory results indicated that the CRM asphalt concrete exhibited lower resilient moduli than the conventional asphalt concrete. The CRM asphalt concrete, however, tended to display higher air void contents than the conventional mixture.

In the field, significant amounts of rutting (> 3.8 mm or 0.15 in) were not present in both CRM asphalt concrete and conventional sections. Also, international roughness index (IRI) revealed no discernable difference between the CRM asphalt concrete and conventional sections.

TH 61 near Forest Lake, Minnesota: Weather conditions were poor at the time construction. The premature failure of the PlusRide crumb rubber sections shortly after placement was attributed to the cold, wet paving conditions. The test sections were removed shortly after placement (17).

I-94 near Collegeville, Minnesota: Both the PlusRide and control sections performed equally. Anticipated improved de-icing and increased friction were not obtained. Conclusions indicated that the performance of the CRM asphalt concrete was similar to the control however, the CRM material was approximately twice the cost (17).

Willard Munger Recreational Trail: The dry process was used to construct two test sections (3 and 6 percent crumb rubber). The gradation was altered for the CRM mixtures by using the coarser side of the standard Minnesota dense gradation band. Mix design data showed that the CRM mixtures had consistently higher voids and required more asphalt cement than the control mixture. Voids were 4.2, 5.7, and 9.1 percent for the control, 3, and 6 percent CRM mixtures, respectively. The asphalt contents increased from 5.0 to 6.5 and 7.7 percent, respectively (18).

Cores were obtained from the all test sections shortly after construction. These results indicated that the air showed a similar trend of higher in-place voids for CRM mixtures: 9.0, 12.6, and 13.0 for the control, 3, and 5 percent CRM mixtures, respectively. Indirect tensile strengths for the CRM mixtures were approximately half of the control mixtures. The control mixtures had an average tensile strength of 483 kPa (70 psi); the strengths were 290 and 206 kPa (42 and 30 psi) for the 3 and 6 percent CRM mixtures, respectively. Although not noted in the report, this reduction in strength could be a function of the significantly higher binder contents in the CRM mixtures and differences in gradation as well as the result of including crumb rubber.

Summary of Field Performance

Table 2.15 summarized the observed pavement performance for all of the field test sections discussed above. This table shows that the most commonly reported benefit is an increase to fatigue cracking. While permanent deformation problems were generally reduce, results for this category of pavement distress were mixed. Little benefit in reducing cold temperature cracking was noted.

Table 2.15. Summary of Asphalt-Rubber Advantages and Disadvantages Based on Field Test Sections.

Agency	Mix Method	Fatigue Resistance	Rutting Resistance	Thermal .Cracking Resistance
Toronto	Wet	+	+	0
Alaska	Dry	+	0	+
California	Wet, Dry	+	+	+
Washington	Dry	0	0	0
Oregon	Dry	+	-	
Florida	Wet	0	0	0
Minnesota	Wet Dry	0 Mixed	0 Mixed	+ (CRM in all lifts) Mixed

+: CRM Improved mix. -: Control Performed Better. 0: All test sections similar at time of report.

CHAPTER THREE

BACKGROUND

When crumb rubber is added to the asphalt cement, with sufficient time and heat, a partially polymer modified asphalt cement is achieved as the rubber is slowly depolymerized (19, pg 203). It is desirable for the asphalt used in the wet process to contain a relatively high percentage of light fractions. This is usually achieved by either adding an extender oil or selecting a lower viscosity grade binder (20). Both have the added advantage of compensating for the increased viscosity when the rubber is added as well as providing sufficient aromatics for rubber reaction without removing key asphalt components. Little work has been done in identifying key asphalt properties for the dry process.

Key rubber properties include the rubber gradation (i.e particle size), and rubber type (21). Finer gradations provide a higher surface area, and hence are more interactive with the asphalt (21). Passenger and industrial tires are each manufactured with different types of rubber. Passenger tires are primarily a combination of synthetic rubber (approximately 26 percent) and natural rubber (approximately 20 percent). Industrial tires are primarily natural rubber (approximately 33 percent) and only 20 percent synthetic rubber. Previous research has suggested that industrial tires produce a more stable and desirable reaction (22). These percentages change with manufacturer, tire type, and technological advances (23). The remainder of the tire is composed of carbon black, plasticizers, and other additives.

Common Viscosity Measurements

One of the most commonly used measures of asphalt-rubber interactions is the Brookfield viscosity measured at various times after the rubber has been added to the asphalt cement. This instrument is a type of rotational viscometer that immerses a disk-shaped spindle into a large volume of asphalt-rubber cement. Huff reported a typical relationship for this viscosity exhibits a peak after a short time, then decreases. He noted that the desired reaction time is that required to achieve the peak viscosity (23).

The Brookfield viscometer, commonly used for evaluating non-Newtonian materials, is capable of measuring fundamental material properties by use of the concentric cylinder configuration. However, the clearance between the rotating cylinder and the outside wall does not provide sufficient clearance (typically a minimum of 10 times the sphere diameter) for the rubber particles. Therefore the rotating disk option for this viscometer was selected. While this configuration has a more complex flow pattern which makes it impossible to determine specific properties such as loss and storage modulus, measurements of torque and rotational speed can be used to develop the material flow index and an estimate of viscosity. This is the approach that was used to estimate the influence of asphalt-rubber interactions on material properties.

Heitzman recommends ASTM D2994 for rubberized tars, a test procedure based on the rotating disk configuration, for determining the viscosity of asphalt-rubber (22). This method uses a Brookfield viscometer and a 0.5-liter (approximately 0.5-quart) sample of material to determine the viscosity at 90, 105, and 120°C with a No.4, No.3, and No.2 spindle, respectively 60 seconds after starting the viscometer. Heitzman modified the ASTM methodology when he recommended requirements for asphalt-rubber binder grades by setting a minimum of 1000 and a maximum of 4000 [sic] poise at 175°C (347°F), a number 3 spindle and 12 rpms (22).

Asphalt-Rubber Interactions

A significant amount of research during the last 25 years in the rubber industry has been devoted to defining the physics of rubber and oil interactions. The following sections have been developed from documented research conducted in the rubber technology field.

Swelling

Most high molecular weight polymers (i.e. rubbers) can show signs of increased volume (i.e., swelling) when immersed in low molecular weight liquids, to varying degrees (19). Polymers that are soluble in water are called hydrophilic. When they are soluble in organic solvents, they are called hydrophobic.

Swelling is a diffusing and not a chemical process, and results from the liquid moving into the internal matrix of the polymer. Strong crosslinks between the rubber chains prevent the liquid from completely surrounding the chains as well as provide a structure that will limit the distortion of the particle. As swelling increases, there is a corresponding degeneration of the polymer properties.

Swelling can be inhibited by increases in filler loading of the rubber. When carbon black is increased in quantity, there is an approximately linear decrease in swelling. This phenomena is enhanced when either channel black or strongly swelling liquids are used (19).

Just after a polymer is immersed in a liquid, the surface of the rubber has a high liquid concentration. As time progresses the liquid moves into the interior portion of the rubber. This movement is controlled by the molecular compatibility of the rubber and liquid, the length of time the rubber is immersed, and the viscosity of the liquid.

Thermodynamics of Swelling

Gibb's free energy of dilution, ΔG_1, is defined as the change in the system resulting from the transfer of one unit quantity of liquid from the liquid phase, into a large quantity of the mixture phase (19). This free energy should be zero for a constant pressure with respect to the transfer of liquid. That is, when swelling has reached equilibrium: $\Delta G_1 = 0$. The total free energy of the dilution can be written as:

$$\Delta G_1 = \Delta H - T\Delta S_1$$

Where:

ΔH = Changes in heat content, cal/mole

ΔS = Changes in entropy of the system due to the transfer of one mole of liquid from the liquid phase to a large quantity of the mixture, cal/(mole °K)

The heat content is related to the internal energy, E, of the system by:
When the pressure, P, is atmospheric, the PV term can be neglected and the internal energy,

$$H = E + PV$$

E, is equal to the heat content, H. When only one of the components of the system has an appreciable vapor pressure (i.e., the liquid), Gibb's free energy of dilution can be defined by:

$$\Delta G = RT \ln \left(\frac{\pi}{\pi_o}\right)$$

Where:

π = Vapor pressure of the liquid component in equilibrium with the mixture at temperature, T, Pa

π_o = Saturation vapor pressure, Pa

T = Absolute temperature, °K

R = Gas law constant (assumes ideal gas), cal/ (mole °K)

When equilibrium swelling has been reached (i.e., ΔG_1 equals zero) then:

$$RT \ln \left(\frac{\pi}{\pi_o}\right) = 0$$

This implies that π equals π_o.

The heat of dilution can either be measured with direct calorimetric measurements or calculated by:

$$\Delta H_1 = \frac{\gamma \left(\Delta \frac{G_1}{T}\right)}{\gamma \left(\frac{1}{T}\right)}$$

The entropy, ΔS_1 of dilution is:

$$\Delta S_1 = \frac{(\Delta H_1 - \Delta G_1)}{T}$$

Figure 3.1 shows experimental data relationships between entropy, the heat of dilution, and Gibb's free energy for unvulcanized natural rubber in benzene. This figure shows that the heat term, ΔH_1 which is indicative of the absorption of heat during mixing, is relatively small and positive. The small ΔH is associated with the lack of strong intermolecular forces (i.e. chemical reaction) (19). The much larger increase in entropy, when compared to the heat of mixing, is consistent with diffusion processes.

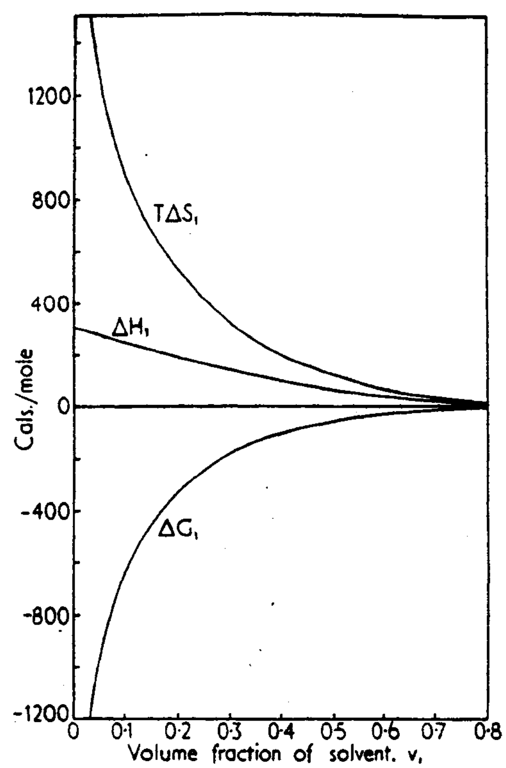


Figure 3.1. Free Energy, Heat, and Entropy of Dilution for System Rubber-Benzene, Calculated from Vapor-Pressure and Osmotic Data (25).

Compatibility

Unvulcanized rubber will dissolve and vulcanized rubber will swell quickly in a compatible liquid (25). Compatibility is determined by comparing the solubility parameters of the individual components:

$$\gamma = (\text{cohesive energy density})^{1/2} = \frac{\Delta H - RT}{\frac{M}{\rho}}$$

Where:

ΔH = Latent heat of vaporization, cal/mole

R = Gas constant, cal/ (liter mole °K)

T = Absolute temperature, °K

M = Molecular weight, g/mole

ρ = Density, g/l

When there is no specific chemical interaction, and in the absence of crystallization, the rubber and liquid are compatible if their solubility parameters are equal. The solubility parameter for rubbers ranges from 7.6 for butyl to 9.9 for nitrile rubbers, most rubbers are towards the upper limit (around 9.0) of this range (19). For example, swelling is generally high for most rubber (except butyl) when immersed in chloroform (δ=9.3) or benzene (δ=9.2), and poor in acetone (δ=10.0) except for nitrile (19). It is the chemical nature of the liquid that defines the amount of liquid that will be absorbed.

Diffusion

The movement of a liquid through the rubber (i.e., penetration) is defined by (17):

$$P = \frac{M_1}{C_o A \sqrt{t}} = \frac{1}{\sqrt{t}}$$

Where:

P = Penetration rate, cm/min$^{1/2}$.

M_t = Mass of liquid absorbed, kg

A = Surface area, cm^3

t = Time, min.

C_o = Concentration of liquid in the surface of the rubber, g/cm^3

l = Depth of swollen layer, cm

The rate of penetration is related to the diffusion coefficient by:

$$D = 1/4\pi P^2$$

Where:

D = Diffusion coefficient, cm^2/min.

P = Penetration rate, cm/min$^{1/2}$.

The length of time for penetration will increase with the square of the depth of penetration. For example, it will take four times as long for a given liquid to penetrate throughout a particle with a diameter of 0.50 cm as it will for one with a diameter of 0.25 cm (17). These relationships confirm previous observations that finer rubber reacts more quickly with a given asphalt cement than when coarser rubber gradations are used.

Viscosity

While the chemical nature of the liquid determines the equilibrium swell value, it is the viscosity of the liquid that determines the rate of swell. The rate of swell increases as the viscosity of the liquid decreases. Figure 3.2 shows the effect of viscosity on the penetration rate, P, into natural rubber for various liquids (19). Based on this relationship, a faster rate of swell should be expected when rubber is added to a softer grade of binder of the same source of binder.

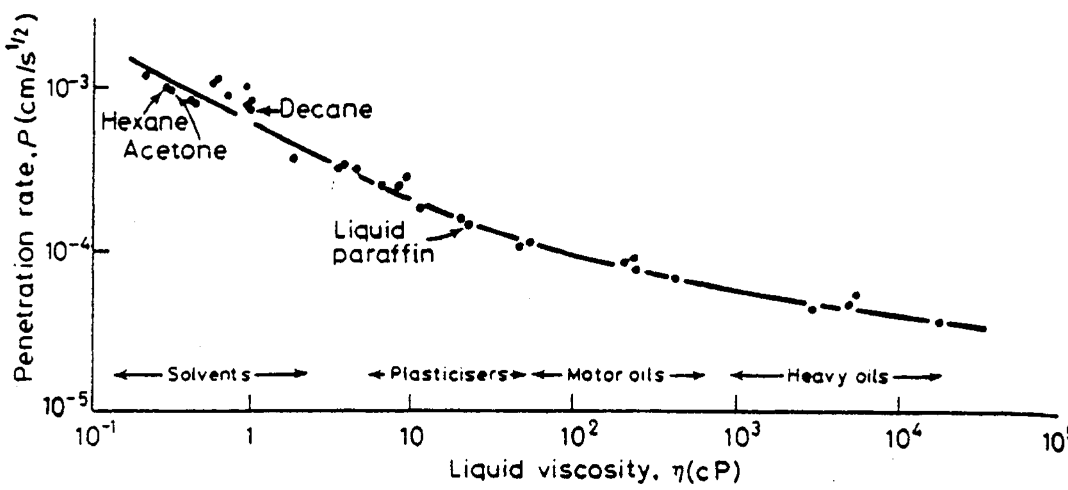


Figure 3.2. Effect of Liquid on the Penetration Rate of Liquids into Natural Rubber From Allen, Lindly, and Payne (1967) Courtesy of Maclaren (19).

Rheology

Rheology is the study of flow and deformation and commonly uses relationships between shear stress and shear strain to quantify material properties. Fluids that have shear stress proportional to shear rate are called Newtonian. This means that viscosities will be consistent over a range of shear rates; typical paving grade asphalt cements are examples of Newtonian materials. Non-Newtonian fluids, however, show viscosities that are dependent upon the shear rate. That is, a viscosity determined for one shear rate will be different than that determined at another shear rate. This dependency of viscosity on shear rate is usually manifested as shear thinning. Polymer-modified asphalts typically fall into this latter category.

The flow index, the slope of the shear stress to spindle rotation speed, is commonly used to represent the Newtonian or non-Newtonian nature of fluids. Typical flow indices for Newtonian fluids are around 1. The flow index decreases (i.e., shear thinning) as the fluid becomes more non-Newtonian (26).

Instruments commonly used to measure both viscosity and develop constitutive models of material properties such as loss modulus and storage modulus are based on measurements from either drag flows or pressure flows. The sliding plate, concentric cylinders, cone and plate, and parallel disk viscometers are examples of test configurations that are based on drag flow (26). All of these tests provide measurements of shear stress, shear strain, strain rate, normal stresses, as well as viscosity. Capillary viscometers such as typical vacuum and kinematic tubes are examples of tests based on pressure flow mechanics. Parameters measured by these tests include measurements of wall shear stress, wall shear rate, first normal stress differences, and viscosity (26).

While all of the above are commonly used instruments in testing asphalt or rubber type products, a combination of the two materials results in discrete particles randomly distributed in a fluid medium, that is, a suspension (26). Factors that are usually considered in the evaluation of a suspension include the volume concentration of particles, particle settling, shape and orientation, interactions, and size distribution. The simplest approach to changes in viscosity due to the volume concentration of particles was developed by Einstein in the early 1900's. Einstein postulated that extra energy will be dissipated because of the modification of the velocity profile around a sphere in a flowing liquid. He assumed a Newtonian incompressible fluid, slow flow, no settling, no slip between the sphere and fluid, rigid spheres, no interactions between spheres, no wall influence, no particle migration, and that the average velocity of the fluid was the same with or without the spheres. This resulted in a simplistic equation for estimating the change in fluid viscosity when a given volume concentration of spheres are added:

$$\eta = \eta_s \left(1 + \frac{5}{2}\phi\right)$$

Where:

η = viscosity of fluid with spheres, poise

η_s = viscosity of fluid, poise

ϕ = volume concentration of spheres

If rubber is incompatible with a given asphalt cement, then the observed increase in viscosity should be close to this theoretical increase in viscosity. Since ground rubber typically has a rough surface texture and irregular particle shape, factors which also increase viscosity, it is expected that this model would only generally approximate a rubber particle in asphalt cement. While a rigorous mathematical approach can address these factors, they require extensive research programs in order to develop the required constitutive model properties. Therefore, only the simplistic evaluation of the impact of volume concentration will be considered in this paper.

OBJECTIVE

The objectives of the asphalt-rubber interaction portion of this study were to evaluate:

1. Testing variability.
2. Effect of increasing percentages and type of rubber on viscosity.
3. Effect of pre-treating rubber on asphalt-rubber interactions.
4. Key asphalt cement components that define a highly reactive and a non-reactive asphalt.

SCOPE

In order to accomplish the above objectives, three experimental designs were developed. The first experiment includes four percentages of rubber (none, 10, 15, and 20 percent by weight of asphalt cement), one rubber gradation, two rubber sources (passenger, and industrial tires), and two asphalt cement grades (85/100, and 120/150 pen grades).

Tall oil pitch, a by-product of wood pulp processing, s identified as a rubber pretreatment and is similar in chemistry to the light fractions of the asphalt. Tall oil pitch is currently used in asphalt compatible areas such as rubber reclaiming tackifiers, limed pitch for asphalt tile, roofing compounds, oil well drilling fluid additives, and the manufacturing process for neoprene. Four levels of rubber pretreatment (none, 2, 5, and 10 percent of tall oil pitch by weight of rubber) were added to the variables in the first experiment, and the percentages of rubber were reduced to one level (20 percent) after a review of the results from the first experiment.

The third experiment required a wide range of asphalt cement chemistry in order to attempt to identify key asphalt components in the asphalt-rubber interactions. Four of the Strategic Highway Research Program (SHRP) materials reference library (MRL) asphalts were obtained for this purpose (27). The experimental design included the four asphalts, one percentage of rubber (20 percent), both rubber types, and two levels of pretreatment (none, and 5 percent tall oil pitch by weight of rubber).

MATERIALS

Asphalt Cements

Two locally available binders, 85/100 and 120/150 penetration grade, were used for the first two experimental designs and were obtained from the Koch refinery in Inver Grove Heights, Minnesota. The physical properties of both asphalt cements are shown in Table 3.1.

The SHRP asphalt cements represent two performance pairs, AAD/AAG, and AAF/AAM. The AAD and AAG are both AR-4000 grade binders from California Coastal and California Valley crude sources, respectively (27). Field performance notes indicate the AAD is susceptible to age hardening. The AAG had the crude treated with lime prior to distillation, its performance exhibits rutting and tenderness problems, and tends to be temperature susceptible. The AAF and AAM are AC-20 asphalts from West Texas Sour and West Texas Intermediate Asphalt crude sources, respectively. Performance notes on the AAF binder indicate that it makes a moisture sensitive mix, ages quickly, and while a very aromatic asphalt with good polymer compatibility, is not generally a well-performing asphalt. The AAM has a high molecular weight neutral phase with low temperature susceptibility, and is generally a good performer. Selected physical properties reported by the SHRP MRL are shown in Table 3.2 (28).

Table 3.1. Asphalt Cement Properties.

Test	85/100 Penetration Grade	120/150 Penetration Grade
Original Properties		
Viscosities: 60°C, Poise 135°C, cSt	1,588 362	908 259
After Rolling Thin Film Oven Test		
Loss on Heating, %	0.0	0.75
Viscosities: 60°C, Poise 135°C, cSt	5,372	2,804 449

Table 3.2. Selected Asphalt Cement Properties Reported by SHRP MRL.

Properties	AAD	AAG	AAF	AAM
Grade	AR 4000	AR 4000	AC 20	AC 20
Crude Source	California Coastal	California Valley	West Texas Sour	West Texas Intermediate
Viscosities: 60°C, Poise 135°C, cSt	1055 309	1862 243	1872 327	1992 569
Penetration, 0.1 mm 25°C, 100 g/5 sec	135	53	55	64
Component Analysis, % Asphaltenes (n-heptane) Aspahltenes (iso-octane) Polar Aromatics Napthene Aromatics Saturates	23.0 3.4 41.3 25.1 8.6	5.8 3.3 51.2 32.5 8.5	14.1 3.1 38.3 37.7 9.6	3.9 NR 50.3 41.9 1.9

NR: Not reported

Rubber

Both the passenger and industrial tire crumb rubber were obtained from the Whirl Air, Inc. Babbit, Minnesota processing plant. This is an ambiently ground crumb rubber; the gradation is shown in Table 3.3.

Table 3.3. Rubber Properties.

Test	Passenger Tires	Industrial Tires
Sieve Sizes	Percent Passing, %	
2.38 mm (No. 8)	100.0	Same
1.12 mm (No. 16)	50.5	
0.50 mm (No. 30)	18.5	
0.30 mm (No. 50)	4.8	
0.15 mm (No. 100)	0.4	
0.075 mm (No. 200)	0	

Tall Oil Pitch

Tall oil pitch was selected as a pretreatment for the rubber based on its past history of use in asphalt-related industries, compatibility with the lighter fractions of the asphalt cement, and economical considerations. Tall oil pitch (DP-3) was provided by Union Camp Corporation of Jacksonville, Florida. Table 3.4 presents the properties reported by the supplier.

Rubber was pretreated by adding the required weight of tall oil pitch (percent by weight of rubber) to the bottom of a large, flat, stainless steel pan, and then heating at 135°C (275°F) for 5 minutes. Crumb rubber was then added on top of the pitch and stirred until none of the pitch remained on the bottom of the pan. Occasionally, this required returning the pan (with rubber and pitch) to the oven for a few minutes and repeating the stirring process. Pretreated rubber was prepared at least 24 hours prior to use; it was stored in sealed plastic bags until used.

The percentages of tall oil pitch used in this study were selected based on conversations with Whirl Air, Inc., who uses this product in the manufacture of rubber mats, and a modification of the aggregate test method for determining specific gravity of fines (ASTM C128). Batches of pretreated rubber were prepared with various percentages of tall oil pitch, the material was poured into the cone, and tamped. The optimum tall oil pitch pretreatment was defined as the percent at which the material just holds its shape. For the passenger tires, the optimum was 5 percent. The 2 and 10 percentages were selected to represent values on both sides of the optimum. The same percent of tall oil pitch was used with the industrial tires so that the level of pretreatment would be consistent throughout the study.

Table 3.4. Tall Oil Properties.

Property	Properties
Composition, %:	
Fatty Acids And Esterified Acids	46
Rosin Acids	20
Unsaponifiables	34
Acid Number	101
Saponification Number	0.6
Specific Gravity	1.03
Viscosities:	
60°C, cSt	3,732
99°C, cSt	260
135°C, cSt	59
Flash Point, °C	216

TESTING

Viscosity and shear rate data collected from the Brookfield rotational viscometer were used to estimate the impact of percent of rubber, rubber type, rubber pretreatment, and asphalt cement chemistry on asphalt-rubber interactions.

Test Methodology

Preliminary experimentation with the Brookfield viscometer identified several procedural problems with Heitzman's recommendations. First, the Brookfield model recommended by the manufacturer for testing asphalt cements is a model HATDV, not an LVT as specified in ASTM D2994. The HATDV has pre-set choices of rotational speeds of 0.5, 1, 2.5, 5, 10, 20, 50, and 100 rpms; the specified 12 rpms was not available. Secondly, a single size spindle could not be used for all materials. Changing spindles was necessary in order to follow the manufacturers recommendation for the percent of torque applied for a given spindle. This resulted in a No. 1 spindle being used for the neat asphalt cements, and a No.2, No.3, and No.4 spindle for the 10, 15 and 20 percent asphalt-rubber binders, respectively.

Temperature control was also a problem. No hot oil bath capable of reaching 175°C was available so the use of various hot plates, heating mantles, and ovens was evaluated for maintaining test temperature. Temperature fluctuations occurred with all heating systems. At this point, advice from industry was sought. Conversations with various laboratory personnel involved with the manufacturing asphalt-rubber binders resulted in the following testing procedures.

Procedure

The neat asphalt cements were heated in a 200°C (392°F) oven for 4 hours, approximately 400 g of asphalt was transferred to a 600 ml beaker, the rubber was added, and thoroughly stirred. The tin foil-covered beaker was then returned to a 185°C (365°F) oven. Prior to testing, the beaker of asphalt-rubber was removed from the oven and stirred vigorously for 30 seconds. The viscometer was set at 100 rpm and the spindle lowered into the fluid for 1 minute to allow the spindle to reach the test temperature. The viscometer motor was then stopped and the fluid stirred briefly. The test was started at the 10 rpm speed and the first reading taken at 10 seconds. The rotational velocities were then increased incrementally to 20, 50, and 100 rpm; readings were taken 10 seconds after each speed change. Viscosity and binder temperature were then determined at intervals of 0.5, 1, 1.5, 2, and 3 hours; a 24 hour measurement, included in the first experiment, was eliminated in subsequent testing due to time constraints. The full test protocol can be found in Appendix A.

One question that arose during testing was if the materials were shear thinning, were they also thixotropic? Figure 3.3 shows typical trends seen throughout the testing; there is a slight tendency towards thixotropy at the higher rubber percentages. This is seen as a lower viscosity measured after the speed has been increased to 100 rpm and is then decreased back to 10 rpm.

Because of this phenomena, the order and time between each shear rate change will influence the results obtained from this test (29). Based on these results, strict stirring and test times were useu to obtain the data presented in this paper.

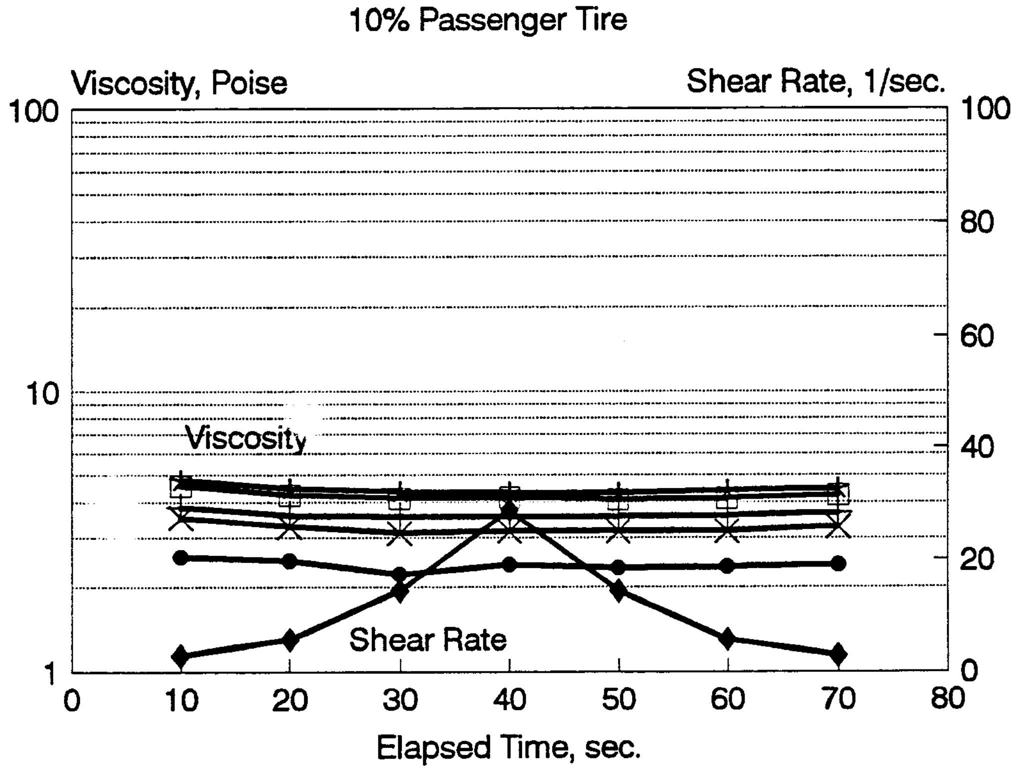


Figure 3.3. Investigation of Thixotropy for Modified Binders.

RESULTS AND DISCUSSION

Throughout this section, increases in viscosity are used as an indicator of asphalt-rubber compatibility. Compatibility is defined in the background section and is a measure of the solubility, and hence swelling of the rubber in asphalt cement.

Non-Newtonian Behavior

Figure 3.4 shows that the slope (i.e, flow index) of the shear stress to shear strain relationship becomes flatter as the concentration of rubber is increased (Table 3.5). The addition of rubber decreases the flow index from 0.95 for 10 percent to 0.65 for 20 percent passenger tire rubber and the 120/150 pen asphalt cement (3 hours). As expected, the unmodified asphalt cement exhibits Newtonian behavior (i.e., n approximately equal to 1). Figure 3.5 shows that while the flow index decreases with rubber concentration (i.e., non-Newtonian behavior increases) aging has little effect.

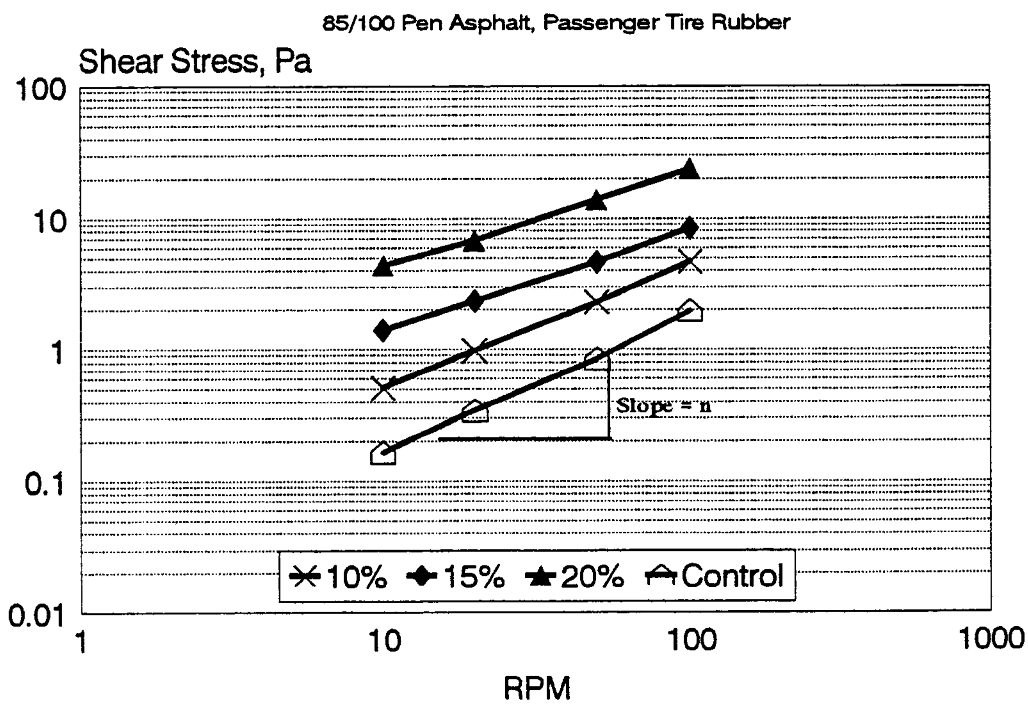


Figure 3.4. Definition of Flow Index.

Table 3.5. Flow Indices for Asphalt and Unmodified Rubber Binders.

Test Time, Hr.	Flow Index, n, for Various Percentages of Rubber							
	85/100 Pen. Asphalt				120/150 Pen. Asphalt			
	0	10	15	20	0	10	15	20
Passenger Tires								
0.5	1.07	0.96	0.86	0.77	1.04	0.96	.085	0.73
1	1.00	0.97	0.82	0.75	1.06	1.00	0.85	0.74
1.5	0.99	0.96	0.80	0.76	1.12	0.[illegible]	0.83	0.72
2	1.01	0.98	0.77	0.73	1.06	0.[illegible]	0.79	0.71
3	1.07	0.95	0.78	0.74	1.09	0.95	0.74	0.65
24	NA	0.91	0.72	0.70	NA	0.89	0.78	0.72
Industrial Tires								
0.5	1.07	1.00	0.89	0.81	1.04	1.01	0.85	NA
1	[illegible]00	1.00	0.90	0.76	1.06	1.02	0.82	0.82
1.5	[illegible].99	1.00	0.88	0.78	0.12	0.99	0.87	0.82
2	1.01	0.98	0.87	0.80	1.06	0.97	0.82	0.76
3	1.07	1.00	0.80	0.78	1.09	0.94	0.81	0.70
24	NA	0.93	0.82	0.79	NA	0.95	0.79	0.70

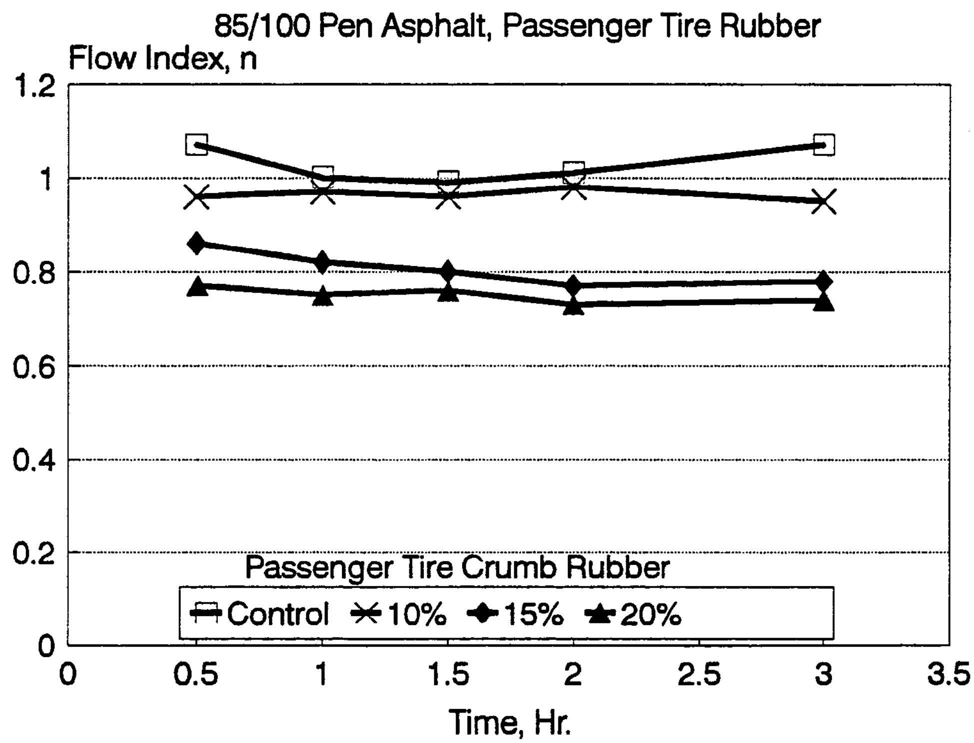


Figure 3.5. Changes in Flow Index with Aging.

Table 3.6 compares shear rates used for determining viscosities with the Brookfield and shear rates associated with conventional Asphalt Institute vacuum tube viscometers (ASTM D2171). Shear rates for the Brookfield viscometer were calculated according to the procedure outlined in reference 27. Shear rates for the Asphalt Institute tubes are reported along with the tube constants on the calibration certificate that accompanies each tube. Shear rates for the Brookfield viscometer range from about 3.5 to 35 sec^{-1} and from 0.62 to 3.65 sec^{-1} for the vacuum viscometer. The lowest shear rate for modified materials tested with the Brookfield were approximately 3 sec^{-1}; this is the highest shear rate achieved with an unmodified asphalt cement in a standard vacuum viscosity tube. For this reason, no comparisons between conventional asphalt cement viscosities and Brookfield viscosities will be made.

Table 3.6. Comparison of Shear Rates

Test Method		Shear Rates, 1/sec.[1]			
		85/100			
		Control	10% Rubber	15% Rubber	20% Rubber
Brookfield	10	3.5	3.1	3.2	3.1
	20	7.0	6.2	6.3	6.3
	50	17.6	15.5	15.9	15.9
	100	35.1	31.0	31.7	31.7
Asphalt Institute[2]	1st Timing Mark	3.65	Not Applicable		
	2nd	1.66			
	3rd	1.06			
	4th	0.78			
	5th	0.62			

1: Shear rates determined for 3 hr test results.
2: Tube shear constant = 160; shear rate is shear constant divided by run time.

Swelling vs. Introduction of Solids

Viscosity increases for the modified binders could be primarily a function of the introduction of sphere-shaped solids into the asphalt cement, instead of swelling due to the solubility of the rubber. Einstein's equation was used to investigate this possibility. Table 3.7 shows that typical asphalt-rubber viscosities are always substantially greater than those predicted by Einstein's equation. For example, the measured viscosities of passenger tire modified binders are approximately 2.3 to 10.5 times greater than the predicted viscosity for 10 and 20 percent rubber, respectively. This indicates that the viscosity increases due to the addition of the rubber are largely the result of swelling due to solubility, rather than merely the inclusion of solid particles.

Table 3.7. Comparison of Viscosity Changes and Einstein's Equation for Increased Viscosity Due to the Introduction of Spheres.

Percent of Rubber	Passenger Tires		Industrial Tires	
	Viscosity from Einstein's Equation[1] (Poise)	Measured Viscosity[2] (Poise)	Viscosity from Einstein's Equation (Poise)	Measured Viscosity (Poise)
85/100 Pen Asphalt				
None	1.14			
10%	1.4	3.2	1.4	2.8
15%	1.6	6.1	1.6	6.3
20%	1.7	17.8	1.7	21.2
120/150 Pen Asphalt				
None	0.94			
10%	1.2	2.4	1.2	2.4
15%	1.3	4.2	1.3	4.3
20%	1.4	10.0	1.4	10.0

1: Viscosity = (1+5/2(1.03/0.99))*(unmodified viscosity)
2: Viscosity at 3 hours, 100 rpms

Testing Variability

Testing variability was a concern both because of the temperature drift noticed during testing and modifications to the ASTM D2994 method. Table 3.8 presents results obtained for replicate tests of 85/100 asphalt modified with 10, 15, and 20 percent of either passenger or industrial tire rubber. These results were obtained at least two months apart and represent both testing and material variability as a new sample of binder was obtained for the replicate. This table shows that the standard deviation appears to be magnitude dependent; a higher viscosity corresponds to a higher standard deviation. When this is the case, the coefficient of variation (CV) is used to express the test variability. The CV for the passenger and industrial tire mixtures are approximately 10 and 15 percent, respectively. These CV's compare favorably (considering the limited data base) with the standard vacuum viscosity measurements (ASTM D2171) with CV's of

7 and 10 percent for within- and between-laboratory results, respectively (24).

Based on the above evaluation of the test method, the modified testing procedure was adopted for the remainder of the study.

Table 3.8. Estimate of Test Variability.

Variable	Standard Deviation	Coefficient of Variation
Passenger Tires		
10%	0.352	11.27
15%	0.628	10.96
20%	1.50	9.02
Industrial Tires		
10%	0.338	12.58
15%	0.80	15.00
20%	1.64	15.95

Effect of Concentration, Binder Grade, and Type of Rubber

Figure 3.6 presents an example of the type and extent of data collected for each combination of asphalt and rubber. The family of curves on the individual graphs represents a shear rate sweep of the viscosity at specified intervals after oven aging. The 85/100 pen asphalt-rubber binders (Figures 3.6a through 3.6c) show an increasing spread between the curves, indicating that increasing the percent of rubber increases the effect of aging on the viscosity. The 120/150 pen asphalt-rubber binders show a substantial increase only after 24 hours of aging (Figures 3.7a and 3.7b). Increasing the concentration of rubber to 20 percent (Figure 3.7c) produces a spread similar to that for the 85/100 pen asphalt-rubber binder. While the spread of the lines is dependent upon the specific asphalt-rubber combination being evaluated, lines for a given combination of asphalt-rubber are approximately parallel at shear rates greater than 5 sec^{-1}. Figure 3.6 also shows that at the 10 percent rubber level the slopes of the curves are relatively flat. The slopes of these lines are reflected in the flow indices (e.g. n=0.95 for 10 percent passenger tire rubber, 3 hours) presented in Table 3.9.

Table 3.9. Flow Indices for Asphalt and Tall Oil Pitch Modified Rubber Binders.

Test Time, Hr.	Percent Tall Oil Pitch Used for Pre-Treatment							
	85/100 Pen. Asphalt				120/150 Pen. Asphalt			
	0	2	5	10	0	2	5	10
Passenger Tires								
0.5	0.75	0.73	0.78	0.76	0.74	0.77	0.71	0.73
1	0.76	0.66	0.78	0.79	0.72	0.76	0.76	0.73
1.5	0.73	0.68	0.79	0.79	0.71	0.69	0.7	0.76
2	0.74	0.70	0.79	0.78	0.65	0.71	0.73	0.76
3	0.70	0.67	0.76	0.75	---	0.63	0.75	0.76
Industrial Tires								
0.5	0.81	0.80	0.84	0.79	---	0.74	0.82	0.85
1	0.76	0.81	0.76	0.88	0.82	0.79	0.80	0.81
1.5	0.78	0.77	0.80	0.82	0.82	0.77	0.79	0.82
2	0.80	0.79	0.81	0.76	0.76	0.78	0.80	0.78
3	0.78	0.77	0.75	0.76	0.70	0.70	0.75	0.77

Based on these observations, the variables in the first experiment will be compared at viscosity values obtained at the 50 rpm level (shear rate of approximately 14 sec^{-1}), after 3 and 24 hours of aging. The aging index, a ratio of the final viscosity to the initial viscosity, was chosen to represent the spread of the family of curves. A shear rate of 50 rpm was selected because it a median shear rate in the parallel line region (Figures 3.6 and 3.7). Only the 3 hour viscosities and aging indices will be compared for the remaining experiments. The 3 hour aging values were selected as most representative of typical field mixing and compaction times.

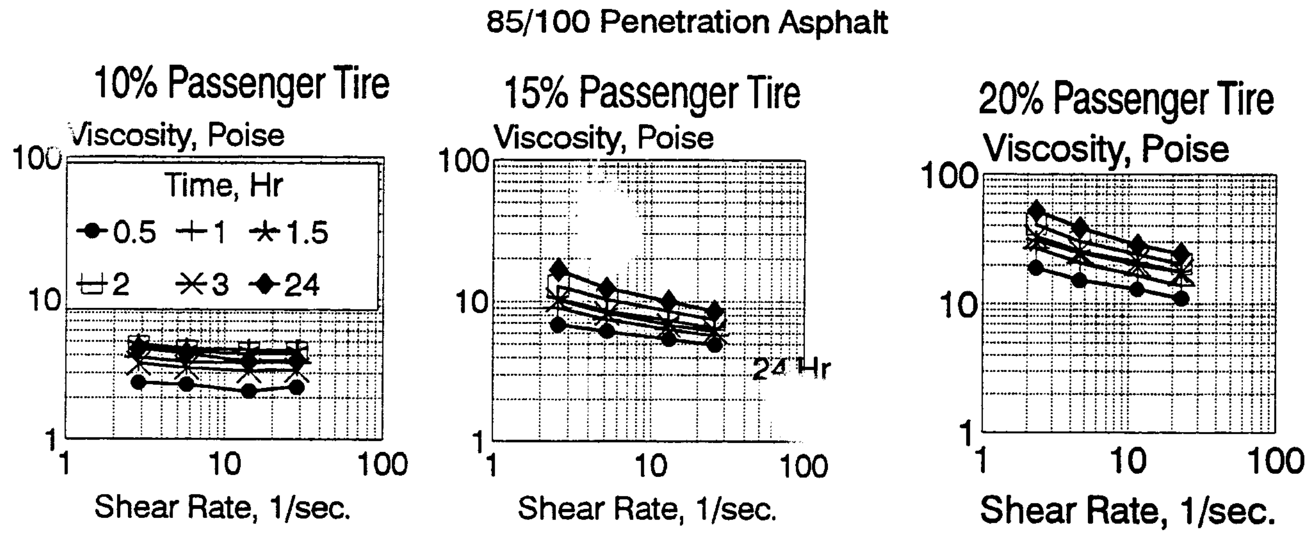


Figure 3.6a. Figure 3.6b. Figure 3.6c.

Figures 3.6a through 3.6c. Influence on Viscosity with Varying Percentages of Passenger Tire Rubber (85/100 Pen Asphalt Cement).

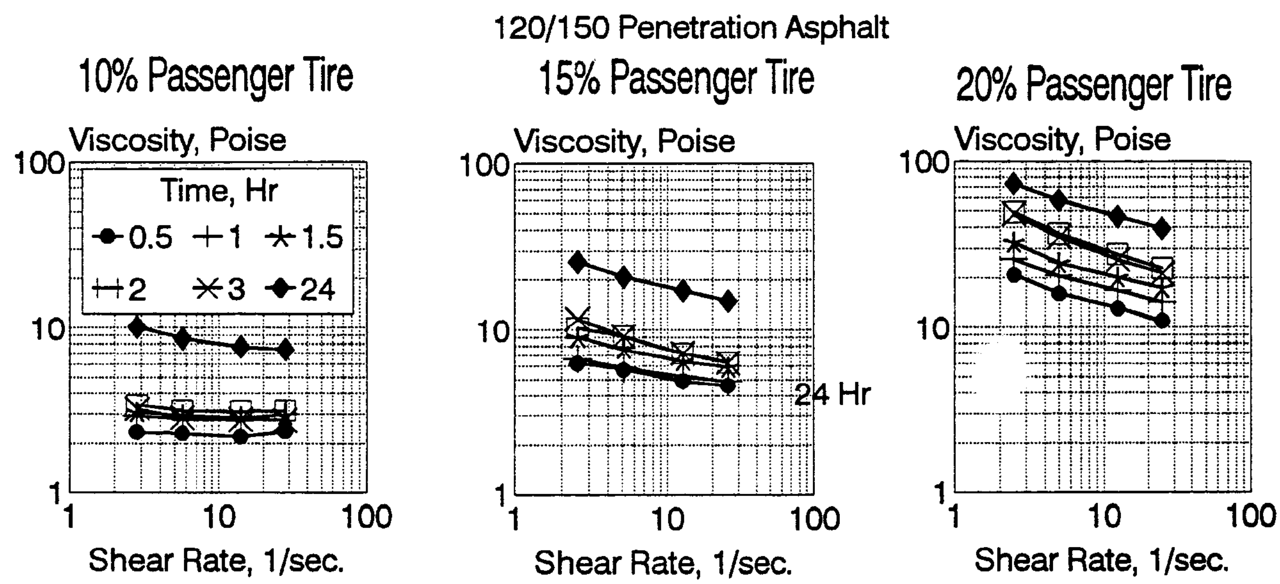
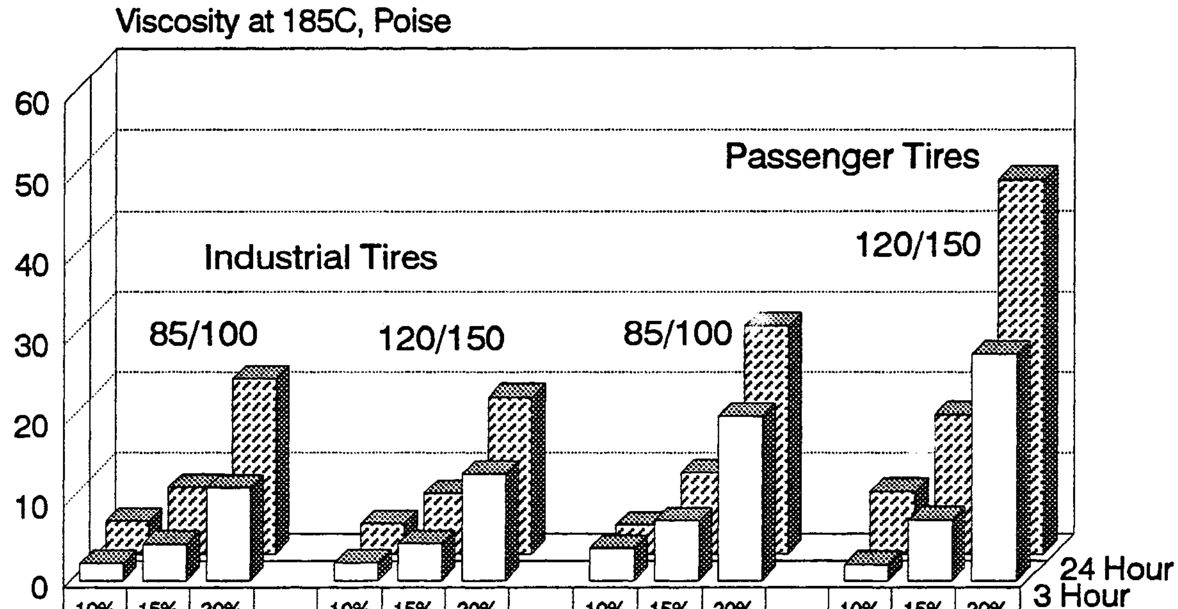


Figure 3.7a Figure 3.7b. Figure 3.7c.

Figures 3.7a through 3.7c. Influence on Viscosity with Varying Percentages of Passenger Tire Rubber (120/150 Pen Asphalt Cement).

Figure 3.8 compares viscosities (50 rpm) at 3 and 24 hours of aging for both the 85/100 and 120/150 pen asphalts, and various percentages of passenger and industrial tire rubber. Viscosities increase substantially as the percent of rubber is increased. The 3-hour and 24-hour viscosities for the 120/150 pen asphalt with the passenger tire rubber showed viscosity increases from 3.62 to 28.2 poise for 10 and 20 percent rubber, respectively. The industrial tires produced binders with 4.08 and 21.6 poise for 10 and 20 percent rubber, respectively (24 hours). While the 24-hour aging always produced the largest viscosities, the 3 hour viscosities exhibited the same trends in increasing viscosities between the types of rubber. Although these trends were consistent for both types of rubber, the magnitude of the industrial tire modified asphalt viscosities were consistently lower than those for the passenger tires. Based upon the general concept of greater compatibility being represented by increased viscosities, it would at first appear that passenger tires are more compatible with asphalt cements. However, it is most likely that the industrial tires with their higher percentage of natural rubbers have a greater tendency to dissolve, rather than swell, in asphalt cements. This would result in a more uniform, more quickly formed, polymer network. It is acknowledged that this assumption should be evaluated using a more fundamental rheological approach such as parallel plate rheometry, but this work was beyond the scope of the current research program.

The softer asphalt cement produced higher viscosities after 24 hours of aging than the 85/100 pen asphalt modified with the passenger tire rubber. This agrees with the information presented in the preceding background section. The grade of binder did not appear to have an effect on the viscosities of binders modified with industrial tire rubber. For example, the 24-hour viscosities for 20 percent industrial tire rubber were 21.6 and 19.4 for the 85/100 and 120/150 pen asphalts, respectively.



	10%	15%	20%	10%	15%	20%	10%	15%	20%	10%	15%	20%
3 Hour	2.12	4.52	11.4	2.2	4.56	13.1	4	7.4	20.3	2	7.5	28
24 Hour	4.08	8.2	21.6	3.74	7.48	19.4	3.62	10	28.2	7.68	17.2	46.4

Percent Rubber

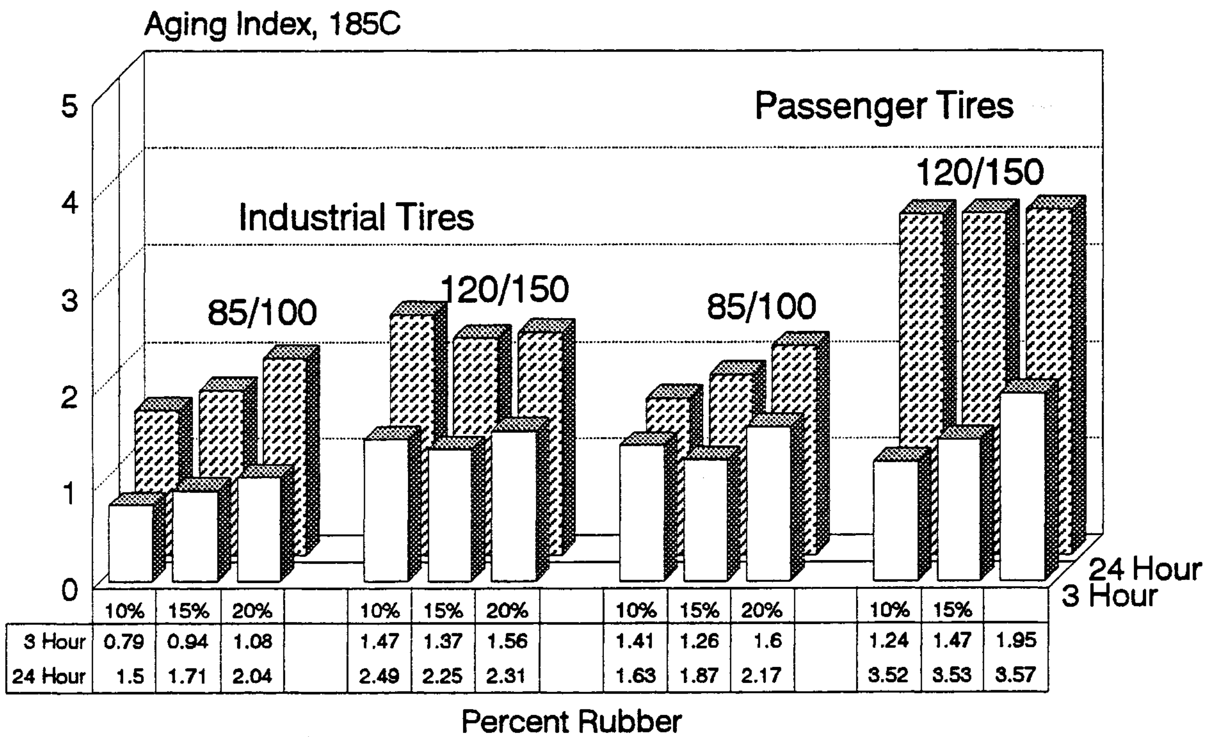
Figure 3.8. Influence of Percent Rubber, Rubber Type, and Asphalt Cement Grade on Viscosity.

Influence of Aging on Viscosity

In order to evaluate the influence of storage time at elevated temperature on viscosity, a ratio of either the 24-hour or the 3-hour viscosity to the initial 30 minute viscosity was calculated. All measurements were taken at the 50 rpm speed. This ratio will be referred to as an aging index and is a function the heat hardening of the neat binder, chemistry changes in the neat binder as the light ends are absorbed by the rubber, rubber swell, and the introduction of carbon black from the rubber into the mixture as the rubber structure is expanded. The plasticizers and softening agents (e.g., extender oils) used in the manufacture of rubber can also be a factor.

Figure 3.9 compares the aging indices calculated for both the 3-hour and 24-hour test results. There was a general trend of increased aging as the percent of rubber increased for the 3 hour index. The 24 hour aging indices showed a similar trend for the 85/100 pen asphalt binders.

However, the 120/150 pen 24-hour indices were uniform and higher than any of those seen for the 85/100 pen binders. This again agrees with the information presented in the background section: lower viscosities mean faster penetration, which in turn means faster swelling.



	10%	15%	20%		10%	15%	20%		10%	15%	20%		10%	15%	
3 Hour	0.79	0.94	1.08		1.47	1.37	1.56		1.41	1.26	1.6		1.24	1.47	1.95
24 Hour	1.5	1.71	2.04		2.49	2.25	2.31		1.63	1.87	2.17		3.52	3.53	3.57

Figure 3.9. Influence of Percent of Tire Rubber on Aging.

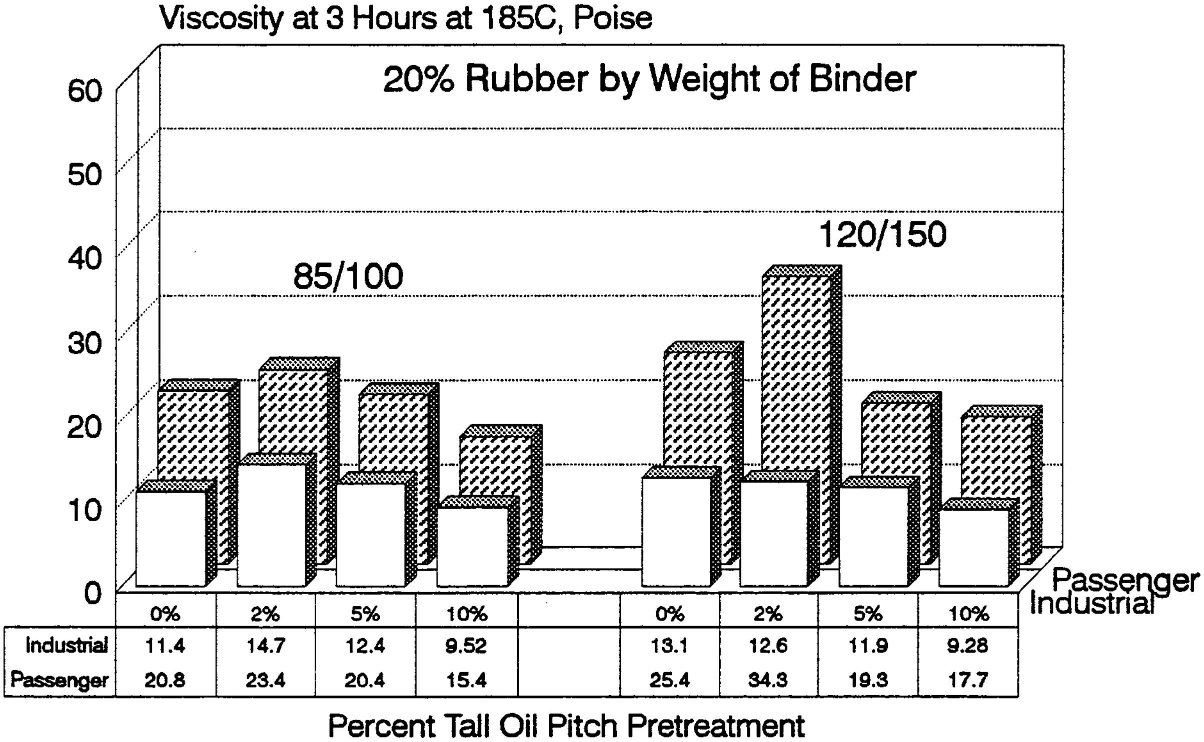
A comparison of the rubber types shows that the industrial tire binders had consistently lower aging indices than passenger tire modified binders. This is most evident when comparing the industrial tire aging indices (less than 2.5) for 20 percent rubber and the 120/150 asphalt to the passenger tire modified binders (greater than 3.5). Again, this could be most likely due to the dissolution of industrial tires rather than swelling. This could not be confirmed within the scope of this research, but is offered as probable hypothesis.

Effect of Pretreatment on Asphalt-Rubber Interactions

The reason for the pretreatment of the rubber was to inhibit or block the penetration of the asphalt cement components into the rubber. If the pretreatment was successful, this should be seen as a reduction of the viscosity increase. Since the ability of a liquid to penetrate the rubber is a function of osmotic pressure (i.e. Gibbs free energy), it is assumed that the liquid vapor pressure generated by the asphalt cement would force the tall oil on or near the surface of the rubber further into the rubber rather than allow the tall oil to modify the asphalt. Even assuming that the tall oil could contaminate the asphalt cement, the viscosities of both the neat binder and the tall oil are less than 1 poise at the test temperature of 185°C; no discernable changes could be measured.

Figure 3.10 shows a general trend of decreasing viscosities with increasing percent of tall oil pitch pretreatment. The exception to this trend was a slight increase in viscosities for the 2 percent tall oil pitch pretreatment. This could indicate that low percentages of pretreatment (below optimum) helps increase the asphalt-rubber interactions for either type of rubber. Viscosities were still consistently higher for the 120/150 pen asphalt when compared to the 85/100 pen asphalt binder; this agrees with trends seen in the previous section. Industrial tires still produced consistently lower viscosity binders than those prepared with passenger tire rubber. There were no consistent trends in the aging index with increasing percentages of tall oil pitch pretreatment.

In summary, these results indicate that pretreating either source of rubber with at least 5 percent of tall oil pitch would reduce the interactions between rubber and either grade of binder.

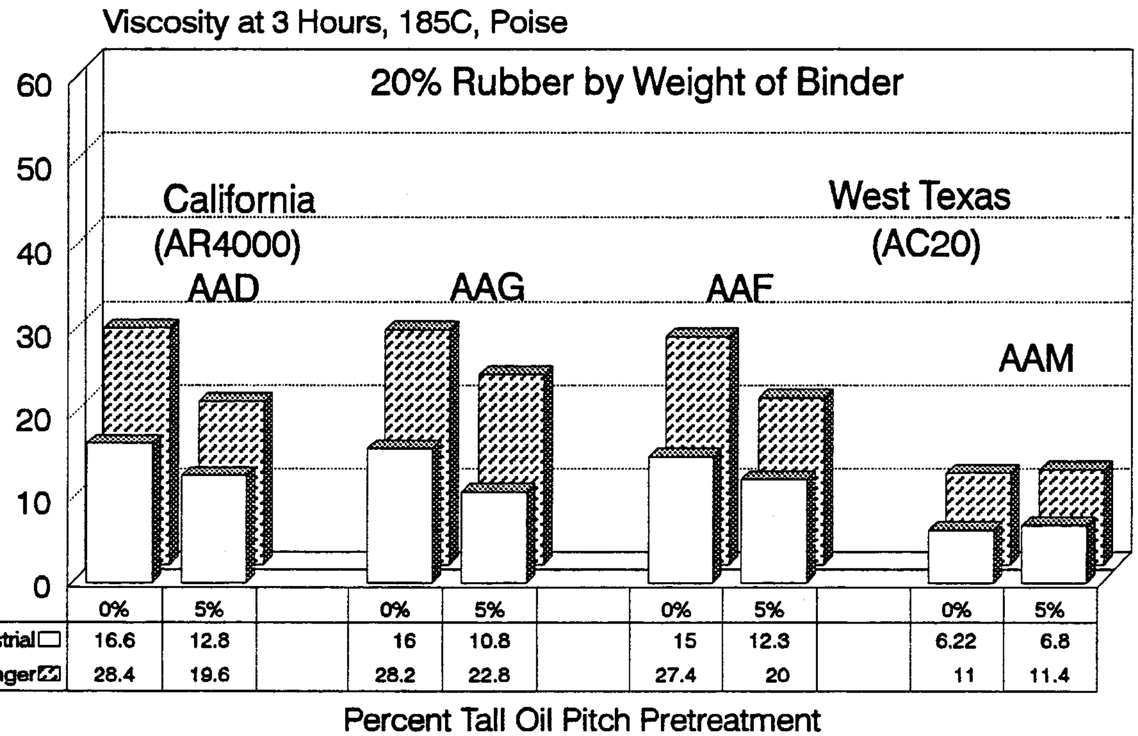


	0%	2%	5%	10%		0%	2%	5%	10%
Industrial	11.4	14.7	12.4	9.52		13.1	12.6	11.9	9.28
Passenger	20.8	23.4	20.4	15.4		25.4	34.3	19.3	17.7

Figure 3.10. Changes in 3.Hr. Viscosity with Pretreatment of Both Passenger and Industrial Tire Rubber.

Effect of Asphalt Chemistry on Compatibility

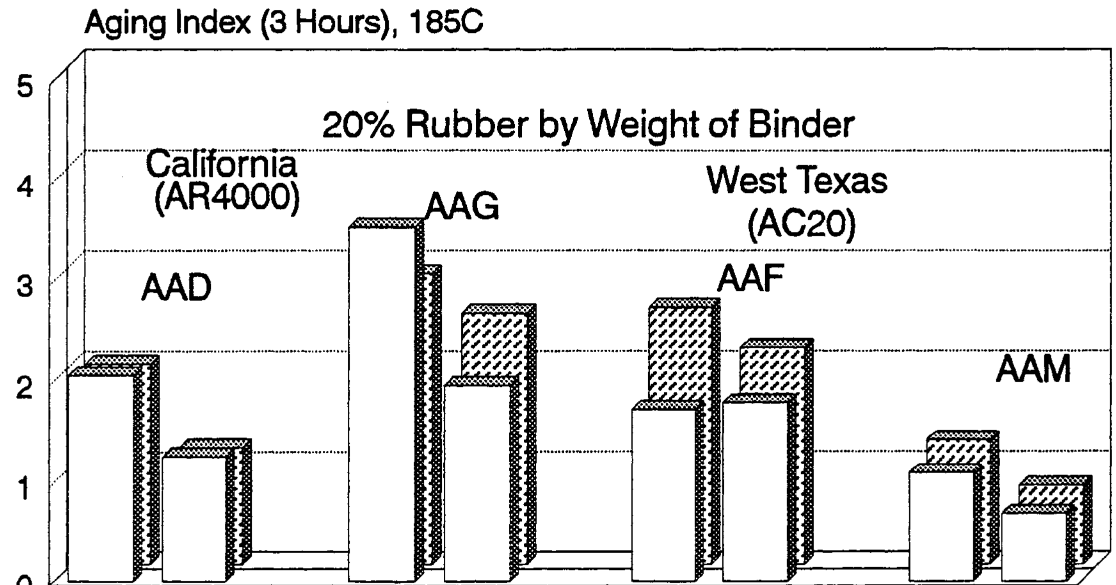
Figure 3.11 shows that the AAD, AAG, and the AAF asphalt-rubber binders produced similar viscosities after 3 hours of aging (50 rpm) for a given type of rubber. This trend was also seen when either rubber was pretreated with 5 percent tall oil. The AAM asphalt-rubber binder viscosities were less than half of any of the other rubber modified binders. Industrial rubber modified binders produce consistently lower viscosities; again the AAM modified asphalts produced viscosities less than half of the other modified binders. Pretreatment of either rubber with 5 percent tall oil consistently reduced the viscosities by about 8 percent of the non-pretreated rubber binders, again with the exception of AAM.



	0%	5%		0%	5%		0%	5%		0%	5%
Industrial □	16.6	12.8		16	10.8		15	12.3		6.22	6.8
Passenger ▨	28.4	19.6		28.2	22.8		27.4	20		11	11.4

Figure 3.11. Changes in 3.Hr. Viscosity with Changes in Crude Sources, and Pretreatment of Rubber (SHRP Asphalt Cements).

Figure 3.12 shows that while the viscosities for the AAD, AAG, and AAF were virtually identical at 3 hours, there were significant differences after extended aging. The AAG showed the greatest increase in viscosity followed by the AAF, AAD, and AAM. If the compatibility of AAD, AAG, and AAF with the rubber was assumed constant, then the differences in the rate of viscosity increase should have been due to the rate of penetration, and hence, the viscosity of the binder. The viscosities of the neat binders at 185°C were 0.67, 0.88, and 0.84 poise for AAG, AAF, and AAD, respectively. This agrees very well with the increased viscosities after aging. It should also be noted that the viscosity of the neat AAM binder was 1.27 poise at 185°C; not only does the rubber appear to be less soluble in this binder, but any solubility was impeded by the much higher viscosity at the aging temperature. Again, the pretreatment of the rubber inhibited the interaction of the rubber and binders.



	0%	5%		0%	5%		0%	5%		0%	5%
Industrial	2.06	1.26		3.54	1.96		1.72	1.79		1.1	0.69
Passenger	2	1.17		2.9	2.5		2.56	2.16		1.25	0.8

Percent Tall Oil Pitch Pretreatment

Figure 3.12. Changes in 3.Hr. Aging Index with Changes in Crude Source, and Pretreatment of Rubber (SHRP Asphalt Cements).

Using the fact that solubility is a function of molecular weight, there should be a relationship between the molecular weight (Table 3.2) of the binders and their compatibility with rubber. Figure 3.13 shows that as molecular weight increased, the viscosity decreased. The 11 poise viscosities for the AAM binder corresponded to a molecular weight of about 1300. Molecular weights of less than 850 produce high viscosities for asphalts modified with 20 percent rubber. When the rubber was pretreated, the influence of asphalt cement molecular weight is decreased.

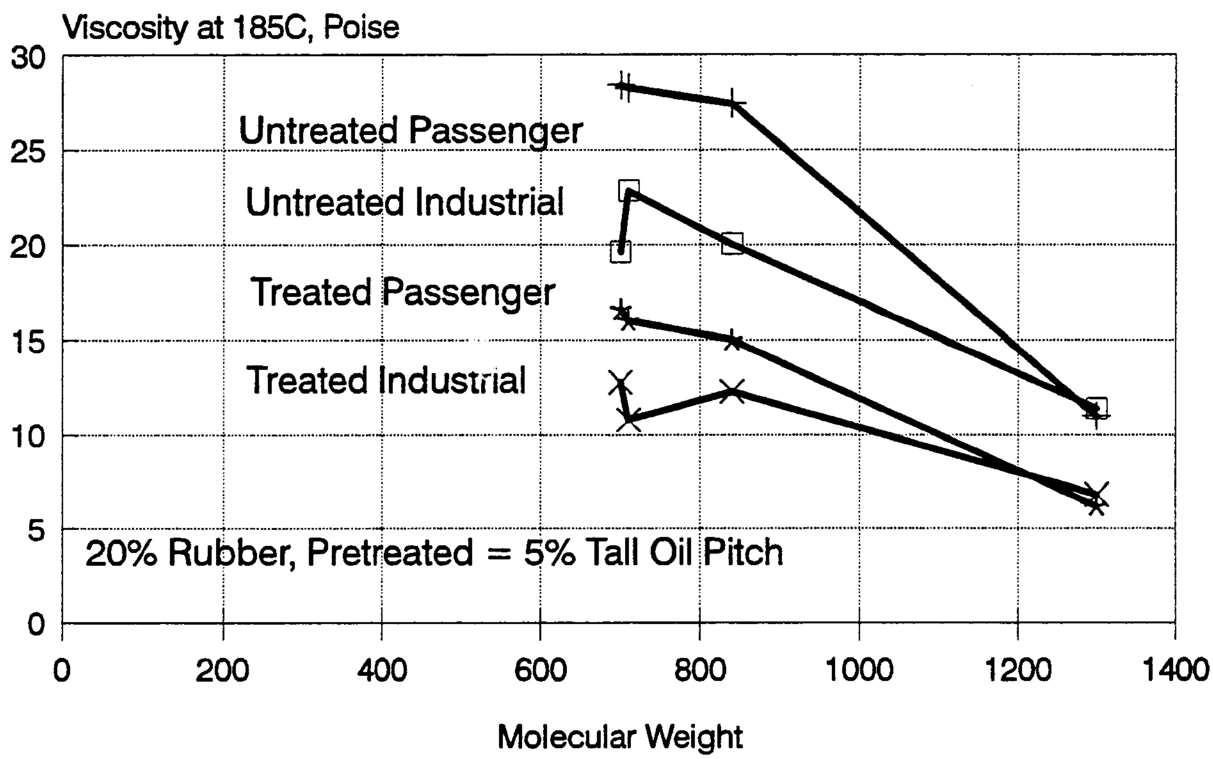


Figure 3.13. Relationship Between Molecular Weight and Viscosity of Modified Binders.

CONCLUSIONS

The following conclusions can be drawn from the data presented in this portion of the study are:

1. Modifications to ASTM D2994 were necessary in order to use this test method with a wide range of asphalt-rubber binders. Modifications include specific material handling procedures, shear rate sweeps at higher rotational speeds, and use of various size spindles.
2. Asphalt-rubber binders prepared with industrial tires have viscosities that are more variable than binders prepared with passenger tire rubber. The coefficient of variation for this study were 10 and 15 percent for passenger and industrial tire modified binders, respectively.
3. Viscosities increase with increasing concentrations of rubber, regardless of type of rubber.
4. Non-Newtonian behavior of asphalt-rubber binders increase with increasing concentrations of rubber.
5. A lower viscosity neat asphalt increases the reaction of the rubber with the asphalt cement when compared to a higher viscosity asphalt from the same refinery.
6. Industrial tire modified binders consistently show less of a viscosity increase than passenger tire rubber. This is possibly due to the dissolution of the industrial tire rubber rather than its swelling in asphalt cements. Further, more fundamental work (i.e., parallel plate rheology) is needed to confirm this hypothesis.
7. Pretreatment of rubber with tall oil pitch reduces the compatibility of the rubber and asphalt cement. The reduction in compatibility increases with increasing levels of pretreatment. A corresponding decrease in aging is seen.
8. Each combination of asphalt and type of rubber produces a uniquely modified binder. Therefore, the compatibility of the rubber and asphalt cement should be part of the quality control testing during construction in order to identify changes in the composition of the crumb rubber source.
9. The compatibility of rubber and asphalt cements can be evaluated by measuring the viscosities of these modified binders with a Brookfield viscometer.

CHAPTER FOUR

The mix design for CRM asphalt concrete with the Marshall method is described in this chapter. The objectives of the mix design for CRM asphalt concrete were to determine: 1) the proportion of rubber to be used in the mixture, 2) the optimum tall oil pitch content to pretreat the crumb rubber, 3) the appropriate aggregate gradation and 4) the optimum asphalt contents. Two concentrations of crumb rubber (3 and 5 percent by weight of aggregate) in the mixture were selected from the literature. To find the optimum tall oil content to pretreat the crumb rubber a cone test for surface moisture of aggregate (ASTM C128) was adopted. Based upon the proportions of crumb rubber, the control gradation (without rubber) was modified to four other gradations (two gradations for each of 3 and 5 percent crumb rubber in the mixture). The Marshall mix-design was adopted to determine the optimum asphalt content in the CRM asphalt concrete mixture.

MATERIALS

Asphalt Cements

The 120/150 penetration grade binders used in the asphalt-rubber interaction study was used to prepare mixtures. The physical properties are shown in Table 3.1.

Aggregates

Two aggregate sources (Lakeland and Granite Falls) were used. The Lakeland aggregate was a river gravel, and Granite Falls material was a crushed granite. The aggregates were sieved into individual fractions and recombined to produce the original gradation shown in Table 4.1 and Figure 4.1. The 9.5 mm (3/8 in) fraction was a crushed granite obtained from Meridian Aggregate in Granite Falls, Minnesota quarry. The 4.75 mm (No.4) through 0.075 mm (No. 200) aggregate fractions were obtained from the Commercial Asphalt, Inc., Lakeland, Minnesota quarry and were a partially crushed river gravel.

Table 4.1. Aggregate Gradations.

Sieve Size	Cumulative Percent Passing, %				
	Control	Gradation A[1] (3% Rubber)	Gradation A[2] (5% Rubber)	Gradation B[1] (3% Rubber)	Gradation B[2] (5% Rubber)
12.5 mm, (1/2-in.)	99.9	99.7	100.0	99.9	99.7
9.5 mm (3/8-in)	78.9	78.2	76.4	76.2	76.8
4.75 mm (No. 4)	61.5	58.6	56.7	58.2	56.3
2.00 mm (No. 8)	49.1	48.5	48.3	45.3	43.3
1.18 mm (No. 16)	38.1	40.1	41.9	35.2	34.4
0.60 mm (No. 30)	26.1	27.1	29.2	22.0	22.5
0.30 mm (No. 50)	17.4	18.4	19.5	13.7	14.3
0.15 mm (No. 100)	11.0	11.6	12.1	7.8	8.3
0.075 mm (No.200)	7.0	7.3	7.5	4.8	5.1

≥ 3/8" : Granite Falls
< 3/8" : Lakeland

[1] Variations of the control gradation; used with 3 percent crumb rubber.
[2] Variations of the control gradation; used with 5 percent crumb rubber.

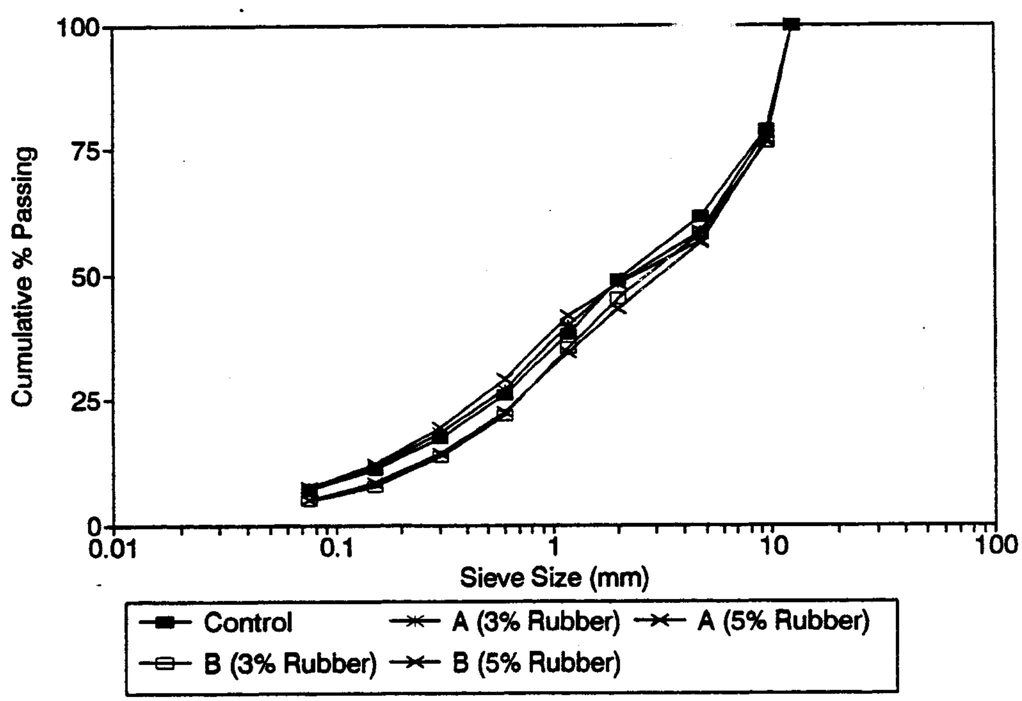


Figure 4.1. Aggregate Gradations.

The physical properties of all aggregate sources are shown in Table 4.2. The minus 0.075 mm (No. 200) material was bag house fines obtained from the Commercial Asphalt, Inc., St. Paul, Minnesota plant. The bag house material was initially substituted for the minus 0.075 mm (No. 200) Lakeland because of difficulty in sieving a sufficient quantity of this material. Table 4.3 shows that there was a significant difference in the properties of the fine materials. Where the Lakeland minus 0.075 mm (No. 200) was non-plastic, the bag house fines have a plasticity limit of around 22 percent. Also, the bag house material was considerably finer than the Lakeland. While there is a significant difference in the two materials, it was felt that because of the low percentage of minus 0.075 mm (No. 200) in the mixtures, this should not cause a problem as the plasticity limit for the combined fines was estimated to be below 2 percent. Generally, fines are considered non-plastic in the range of 0 (i.e., non-plastic) to 4 percent.

Rubber

The crumb rubber (passenger tire) that was used in the asphalt-rubber interaction study was used in this study. This crumb rubber was divided into two groups (pretreated and untreated) depending on the treatment condition (pretreated and untreated rubber). The gradations of crumb rubber are shown in Table 4.4.

Tall Oil

Tall oil pitch, as used in the asphalt-rubber interaction study, was used to pretreat the crumb rubber. The tall oil content was 5 percent by weight of rubber. The physical properties are shown in Table 3.4.

Table 4.2. Physical Properties of Aggregates.

Aggregate	Bulk Specific Gravity	Bulk Specific Gravity, SSD	Absorption Capacity, %
Lakeland	2.582	2.650	2.6
G.F[1]	2.648	2.660	0.4

[1] Granite Falls

Table 4-3. Properties of Minus No. 200 Material.

Properties	Lakeland Minus No. 200	Bag House Fines[1]
Atterberg Limits		
Liquid Limit	19.6%	35.2%
Plastic Limit	NP	22.1%
Plasticity Index	19.6%	13.1%
Hydrometer Analysis, % Finer		
Particle Size (mm)		
0.0327	23.4	56
0.0210	18.3	54
0.0123	13.1	52
0.00887	10.5	49
0.00631	10.5	47
0.00314	9.0	37
0.00132	7.6	19.5

[1] Hydrometer analysis values estimate from gradation graph so that a direct comparison can be made between the types of fines.

Table 4.4. Crumb Rubber Gradation.

Sieve Size	Percent Passing	
	Treated	Untreated
4.75 mm (No. 4)	99.85	100.00
2.00 mm (No. 8)	98.87	99.99
1.18 mm (No. 16)	51.68	50.51
0.60 mm (No. 30)	17.86	18.53
0.30 mm (No. 50)	2.20	4.77
0.15 mm (No. 100)	0.07	0.36
0.075 mm (No. 200)	0.00	0.00

PRETREATMENT OF CRUMB RUBBER

The purpose of the pretreatment of crumb rubber with tall oil was to prevent the crumb rubber from absorbing light and fractions of the asphalt binder during and after mixing. The crumb rubber was mixed with the tall oil before it was combined with the aggregate and asphalt binder. To determine the optimum tall oil content several tall oil contents (3 to 8 percent by weight of crumb rubber with a 1-percent increment) were tested with the cone test for adhesion (ASTM C128).

The gradation of pretreated crumb rubber was almost the same as that of untreated crumb rubber as shown in Table 4.4. The details of the crumb rubber treatment is presented in Appendix B.

AGGREGATE GRADATIONS

The aggregate gradations for the CRM asphalt concrete mixtures were obtained from the modification of the original gradation (without rubber). The principle of this modification was to reduce some portion of aggregate whose volume was the same as that of the designed portion of crumb rubber from the original gradation. It was assumed that the range of reduction in aggregate sizes was the same as that of the added crumb rubber sizes. It was also assumed that the volume of original aggregate gradation was the same as that of the modified aggregate gradation including the crumb rubber.

For mix design testing, five aggregate gradations (control, gradation A-3, gradation A-5, gradation B-3, and gradation B-5), which were variations of the typical Minnesota gradation, were used. These gradations are shown in Table 4.1 and Figure 4.1.

MIXTURES

For each aggregate gradation and crumb rubber content, the Marshall method was used to determine the optimum asphalt content. To obtain the target air void content of 4 percent several asphalt contents (3.5 to 5.5 percent by weight of aggregate for the control mixture and 4 to 8 percent for the crumb rubber mixtures) were compacted with 50 blows per side at a temperature of 135 °C (275 °F). Three samples were used to represent one test set for each asphalt content. With test methods from ASTM, bulk specific gravity (ASTM D2726), Marshall stability and flow (ASTM D1559), theoretical maximum specific gravity (ASTM D2041), and air void content (ASTM D3203) were determined. These values are listed in Table 4.5.

Also, the voids in mineral aggregate (VMA) in each specimen was determined. The VMA is defined as the intergranular void space between the aggregate particles of a compacted asphalt concrete mixture (specimen) that includes the air voids and the effective asphalt content, expressed as a percent of the total volume. Since the VMA is calculated as a percentage of the bulk volume of the compacted asphalt concrete mixture (specimen) it can be obtained by subtracting the volume of the aggregate determined by its bulk specific gravity from the bulk volume of the compacted asphalt concrete mixture (specimen). The formula to calculate the VMA is expressed as:

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}}$$

Where:

G_{sb} = bulk specific gravity for the total aggregate

G_{mb} = bulk specific gravity of compacted asphalt concrete mixture (specimen)

G_s = aggregate, percent by total weight of mixture

Table 4.5. Mix Design Results at Optimum Binder Content.

Gradation	Percent Crumb Rubber	Opt. AC %	Air Voids %	Marshall Stability kN (lb)	Flow mm (0.01 in)	VMA %	Unit Weight kg/m^3 (lb/ft^3)
Control	None	4.3	4.0	14.68 (3300)	1.5 (6)	14.2	2449.5 (152.9)
	3%, Untreated	6.9	4.0	5.57 (1253)	4.3 (17)	15.9	2244.4 (140.1)
	3% Pretreated	6.7	4.0	5.69 (1278)	4.3 (17)	15.9	2242.8 (140.0)
	5% Untreated	7.9	4.0	4.23 (950)	5.6 (22)	20.8	2169.1 (135.4)
	5% Pretreated	8.1	4.0	5.12 (1151)	5.1 (20)	17.2	2170.7 (135.5)
Grad. A	None	4.0	4.0	14.46 (3250)	1.5 (6)	10.4	2435.0 (152.0)
	3%, Untreated	6.5	4.0	7.53 (1692)	3.8 (15)	13.9	2287.7 (142.8)
	3% Pretreated	6.0	4.0	9.39 (2111)	3.3 (13)	14.0	2284.5 (142.6)
	5% Untreated	7.5	4.0	4.99 (1123)	4.6 (18)	18.2	2185.1 (136.4)
	5% Pretreated	8.5	4.0	4.25 (956)	5.3 (21)	18.5	2162.7 (135.0)
Grad. B	None	4.5	4.0	10.95 (2462)	1.8 (7)	12.5	2380.6 (148.6)
	3%, Untreated	7.3	4.0	4.45 (1000)	3.8 (15)	15.7	2260.4 (141.1)
	3% Pretreated	7.3	4.0	5.12 (1150)	4.1 (16)	16.4	2230.0 (139.2)
	5% Untreated	8.2	4.0	4.04 (908)	4.8 (19)	17.5	2114.6 (132.0)
	5% Pretreated	7.7	4.0	4.25 (956)	5.1 (20)	17.5	2149.9 (134.2)

In this research, three different types of aggregate (fine, coarse, and crumb rubber) were used to make the specimens. The value of G_{sb} (bulk specific gravity for the total aggregate) was calculated with following formulas:

$$G_{sb} = \frac{P_{wf} + P_{wc} + P_{wr}}{P_{wf}/G_f + P_{wc}/G_c + P_{wr}/G_r}$$

$$P_{wf} = \frac{P_{vf}G_f}{P_{vf}G_f + P_{vc}G_c + P_{vr}G_r}$$

$$P_{wc} = \frac{P_{vc}G_c}{P_{vf}G_f + P_{vc}G_c + P_{vr}G_r}$$

$$P_{wr} = \frac{P_{vr}G_r}{P_{vf}G_f + P_{vc}G_c + P_{vr}G_r}$$

where:

P_{wf}, P_{wc}, P_{wr} = percentages by weight of fine and coarse aggregate, and crumb rubber, respectively,

P_{vf}, P_{vc}, P_{vr} = percentages by volume of fine and coarse aggregate, and crumb rubber, respectively,

G_f, G_c, G_r = Bulk specific gravity of fine and coarse aggregate, and crumb rubber, respectively.

The values of VMA are listed in Table 4.5.

It was noticed that all specimens with crumb rubber had a dome on the top side of the sample; conventional samples did not have this shape. This resulted from the beveled face of the hammer, the rotation of the mold during compaction, and the upward pressure within the sample due to the rebound of the crumb rubber. This observation indicated that these mixtures could be difficult to compact. Therefore, a study was initiated to determine the compactibility of crumb rubber mixtures. The procedure for preparing the asphalt-rubber mixtures is presented in Appendix B.

COMPACTIBILITY

Once the optimum asphalt content for the 120/150 penetration asphalt cement had been determined, a set of three specimens of the CRM asphalt concrete was prepared for gradations A and B, and 3 and 5 percent crumb rubber. One specimen was compacted with 15 blows per side, the second and third specimens were compacted with 30 and 75 blows per side, respectively. The air void contents were determined and a relationship between compactive effort (i.e, number of blows per side) and air void contents is listed in Table 4.6 and shown in Figure 4.2.

Table 4.6. Relationship Between Compactive Effort and Air Voids.

Mixture	No. of Blows (per Side)	Void Content, %	
		Gradation A	Gradation B
3 % Untreated	15	12.9	6.1
	30	9.6	4.4
	75	5.1	2.0
3 % Pretreated	15	11.8	8.1
	30	9.6	5.5
	75	4.6	4.1
5 % Untreated	15	11.2	9.4
	30	8.2	7.8
	75	3.2	1.7
5 % Pretreated	15	8.0	8.3
	30	4.9	7.4
	75	1.1	2.8

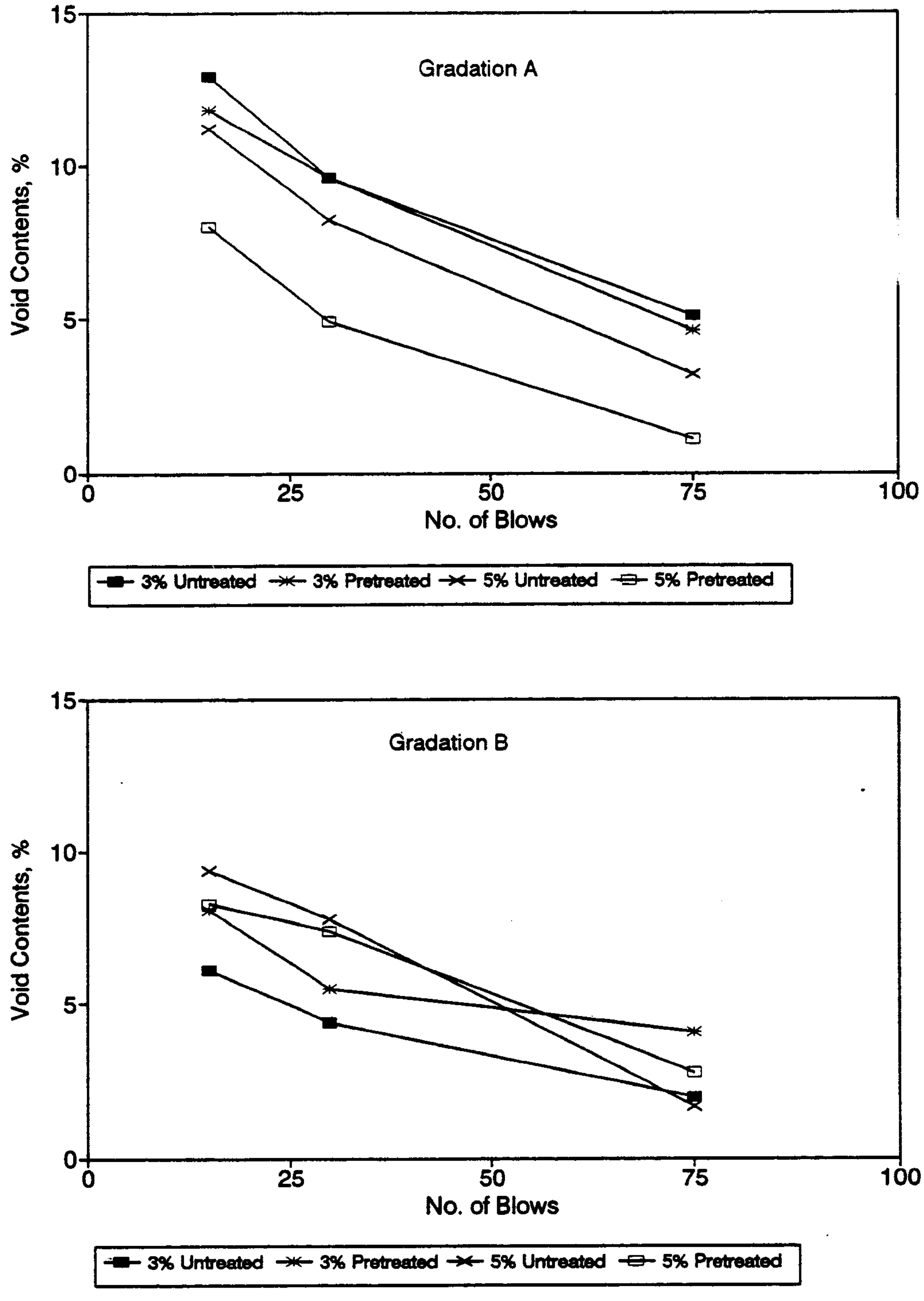


Figure 4.2. Relationship Between Compactive Effort and Air Voids.

These show that the air voids decrease with increasing compactive effort. Both gradations A and B behaved as expected. In most cases, lower voids were easier to obtain for gradation B (coarser) compared to gradation A except when the asphalt-rubber concrete contained 5 percent pretreated crumb rubber.

RESULTS AND CONCLUSIONS

The results of mix design at optimum asphalt content for asphalt-rubber concrete are shown in Table 4.5. Since the air void content was the first consideration, the mix design results were tabulated based upon the four percent target air void content. The complete mix design results for all gradations are listed in Appendix C. To determine the proper aggregate gradations and their optimum asphalt contents for three rubber contents (0, 3, and 5%) CRM asphalt concrete the Marshall design criteria (29) shown in Table 4.7 were employed.

Based upon the results of the mix design for CRM asphalt concrete, following conclusions were made:

1. Two proportions of crumb rubber (3 and 5 percent by weight of aggregate) were selected.
2. The optimum tall oil content of 5 percent (by weight of crumb rubber) was determine with the cone test for surface adhesion (ASTM C128).
3. At least 3 aggregate gradations (control gradation for 0 percent, gradation A for 3 percent and gradation B for 5 percent crumb rubber) with pretreated crumb rubber would be used for laboratory test.
4. The optimum asphalt contents were 4.7, 6.0, and 8.0 percent by weight of aggregate for 0 (control gradation), 3 (gradation A) and 5 percent (gradation B) crumb rubber mixtures, respectively.
5. Lower voids were easier to obtain for gradation B compared to gradation A.

Table 4.7. Marshall Mix Design Criteria (29).

Mix	Light Traffic	Medium Traffic	Heavy Traffic
		Min. Max.	Criteria
# of Blow	35	50	75
Stability, N (lb)	2224 (500)	3336 (750)	6672 (1500)
Flow, mm (0.01 in)	8 (2) 20 (5)	8 (2) 18 (4.5)	8 (2) 16 (4)
% Air Voids	3 5	3 5	3 5
VMA	Dependent Upon Top Size of Aggregate		

CHAPTER FIVE

The laboratory experimentation is described in this chapter. This chapter contains five sections. First section of this chapter states the objectives of the laboratory tests. The test programs are described in the second section; the tests and response variables and their levels are specified. The third section discusses the characteristics and properties of the materials used in the laboratory tests. The fourth section presents the test results and analysis. Based upon the fourth section, some conclusion are made in the last section.

OBJECTIVE

The objective of the laboratory tests was to conduct a preliminary evaluation of the fundamental properties of CRM asphalt concrete mixtures prior to the construction of field test sections. A secondary objective was to evaluate the suitability of standard laboratory tests for determining key properties of asphalt-rubber concrete mixtures. The results of the laboratory tests were used for the design and construction of the field test section.

TEST PROGRAM AND EXPERIMENTATION

To accomplish the objectives described above, two simple experimental methods were selected: the indirect tensile test (low temperature behavior), and diametral resilient modulus test (temperature susceptibility) on cylindrical specimens of 100 mm (4 in) diameter and 64 mm (2.5 in) height. Three specimens were prepared for each test condition.

Since the test variable selected for these tests was temperature (-18 and 1 °C (0 and 34 °F) for the indirect tensile test and -18, 1, 25, and 40 °C (0, 34, 77, and 104 °F) for the diametral resilient modulus test) the environmental chamber was regulated to the testing temperature for at least 10 minutes before installing the conditioned specimens. The loading speed of 50 mm/min (2 in/min) for the indirect tensile test since the loading rate must be sufficient fast to avoid the loading rate affect to the tensile strength. The loading frequency of 1 Hz was selected for the diametral resilient modulus test since asphalt mixtures are not sensitive to changes in frequency if the loading frequency is less than or equal to 1 Hz (30). The test programs are summarized in Table 5.1.

Table 5.1. Test Program.

Test	Temperature (°C)	Loading
Indirect Tensile	-18, 1	50 mm/min
Resilient Modulus	-18, 1, 25, 40	1 Hz

The response variable measured in the indirect tensile test was the horizontal displacement with applied load. This was used to calculate the horizontal strain. The tensile strength was calculated as:

$$S_t = \frac{2P_{max}}{\pi d t}$$

where:

S_t = tensile strength, kPa (psi)

P_{max} = applied load, kN (lb).

d = diameter of the specimen, m (in)

t = height or thickness of the specimen, m (in)

The response variables measured in the diametral resilient modulus test were the horizontal and vertical displacements with time. These could be used to calculate the resilient modulus for the tested materials. However, since the Poisson's ratio was assumed to be 0.2 for either -18 °C (0 °F) or 1°C (34 °F) test temperatures, and 0.35 and 0.5 for 25 and 40 °C (77 and 104 °F), respectively, the vertical displacements were not used to calculate the resilient modulus. The equation for calculating the resilient modulus is:

$$M_R = \frac{P[\nu + 0.2734]}{t u_x}$$

where:

M_R = Resilient modulus, kPa (psi)

P = applied load, kN (lb).

ν = Poisson's ratio

t = height or thickness of the specimen, m (in)

u_x = horizontal displacement, m (in)

A closed loop servo-hydraulic MTS (Material Testing Systems, Inc) was used for both the indirect tensile test and resilient modulus test. The analytical discussions of the indirect tensile test and resilient modulus test were presents in Appendix E.

MATERIALS

Asphalt Cements

The same 85/100 and 120/150 penetration grade binders used in the asphalt-rubber interaction study were used to prepare the asphalt-rubber concrete specimens The physical properties were shown in the previous section in Table 3.1.

Aggregates

Two types of aggregate (Lakeland and Granite Falls) were used. These were the same aggregates which were used in the mix design (chapter four). A total of three gradations were selected from the mix; control gradation for 0 percent rubber mixture, gradation A for 3 percent rubber mixture, and gradation B for 5 percent rubber mixture. All gradations were variations of the typical Mn/DOT 2331, Type 41 gradation (Table 4.1, Figure 4.1). The physical properties of aggregates were shown in Table 4.2.

Rubbers

The same crumb rubber (passenger and industrial tire) that was used in the asphalt - rubber interaction study was also used in this study. The crumb rubber was conditioned with 5 percent tall oil pitch by weight of rubber. The details of the crumb rubber treatment are presented in Appendix B and the gradations of the pretreated and untreated rubber are shown in Table 3.3. The gradations of crumb rubber from the passenger tire and industrial tire were identical when the treatment condition was same.

Mixtures

Three types of asphalt-rubber concrete mixtures were evaluated in the laboratory. Based upon the results of the mix design, the optimum asphalt contents were determined. The asphalt content, rubber type and content, and gradation for each mixture type is listed in Table 5.2.

Table 5.2. Testing Mixtures.

Mixture Type	Gradation	Asphalt Content
Control	Control	4.3
PA[1] 3% Rubber	A	6.5
PA 5% Rubber	B	8.2
IN[2] 3% Rubber	A	6.5
IN 5% Rubber	B	8.2

[1] Passenger tire [2] Industrial tire

Aggregate from individually sized stockpiles were batched to form the selected gradation. Prior to mixing, the batched aggregate were dried in a 135 °C (275 °F) oven for at least 12 hours. A Hobart 20 quart mixer with a wire whip was used to mix the aggregate, crumb rubber (stored at room temperature), and asphalt cement for three specimens at one time. The mixtures were stored at 135 °C (275 °F) for three hours prior to compaction; this was per the SHRP mix design recommendation for simulation of short term aging. The 100 mm (4 in) diameter molds were preheated at 135 °C (275 °F); the face of the 4.5 kg (10 lb) hammers were also heated on a large hot plate. The mixture was then carefully added into the mold and then rodded 25 times. A rotating base, bevel head Marshall compactor was used to compact the specimens (50 blows per side). The specimens were allowed to cool prior to extruding and conditioned at a testing temperature for at least 24 hours before testing. The detail procedure for specimen preparation is given in Appendix C.

RESULTS AND DISCUSSION

Indirect Tensile Test (Low Temperature Behavior)

Figures 5.1 and 5.2 present averaged test results of the indirect tensile test at -18 and 1° C (0 and 34° F), respectively. Since three specimens were one set for the test, there were three test results per test condition. The complete test results are shown in Appendix F.

Table 5.3 shows the maximum fracture tensile strength as well as the corresponding horizontal deformations. In general, the tensile strengths decrease when crumb rubber is added to the mixtures. However, at cold temperatures this usually indicates that stress is being dissipated by viscous flow. Even at the fast loading rate of 50 mm/min (2 in/min), the increased ability of the crumb rubber mixtures to strain can be seen.

Figure 5.3 compares the horizontal strains for the 85/100 and 120/150 pen asphalt cement mixtures. This figure shows that the ability of the CRM mixtures with the 85/100 to strain increased from 100 and 300 percent for the 3 and 5 percent of either type of crumb rubber, respectively, at the colder test temperature. As the test temperature increased, there was less of a difference between the mixtures: the strains increased from 50 to 110 percent for 3 and 5 percent rubber, respectively. This figure also shows that there was little difference between either grade of asphalt cement at the colder test temperature. However, as the temperature increased, the 120/150 pen asphalt cement produced mixtures with a substantially greater ability to deform compared to the 85/100 pen asphalt cement mixtures.

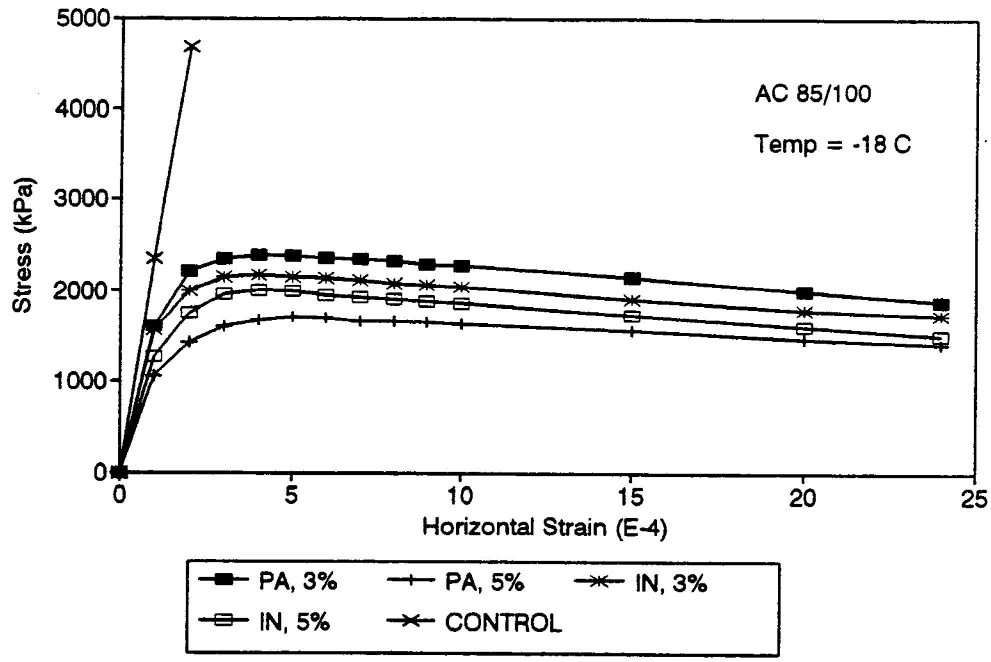


Figure 5.1. Test Results for Indirect Tensile Test at -18°C (0°F).

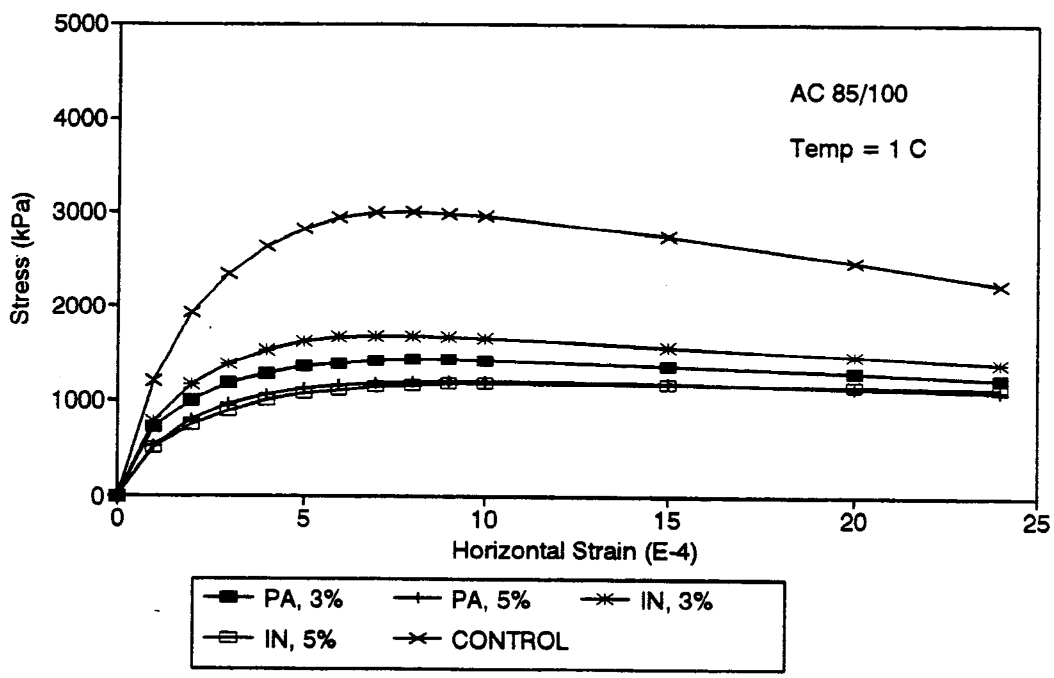


Figure 5.2. Test Results for Indirect Tensile Test at 1°C (34°F).

Table 5.3. Low Temperature Behavior.

Asphalt Cement Grade	Type of Crumb Rubber	Percent of Pretreated Crumb Rubber %	Air Voids %	-18°C (0°F)		1°C (34°F)	
				Maximum Tensile Strength kPa (psi)	Total Horizontal Strain (x10^{-6})	Maximum Tensile Strength kPa (psi)	Total Horizontal Strainμm (x10^{-6})
85/100	None	None	4.8	4094 (594)	(170)	3135 (454)	(590)
	Passenger	3	7.5	2325 (337)	(340)	1460 (212)	(900)
		5	8.9	1688 (245)	(620)	1223 (177)	(1,260)
	Industrial	3	7.4	2167 (314)	(380)	1643 (238)	(870)
		5	9.1	2020 (294)	(450)	1191 (173)	(1,250)
120/150	None	None	4.2	4853 (704)	(210)	2491 (361)	(1,390)
	Passenger	3	7.2	1666 (242)	(360)	1136 (165)	(1,118)
		5	8.5	1401 (203)	(750)	884 (128)	(1,580)
	Industrial	3	7.6	2005 (291)	(390)	1506 (218)	(1,300)
		5	9.5	1464 (212)	(630)	980 (142)	(1,590)

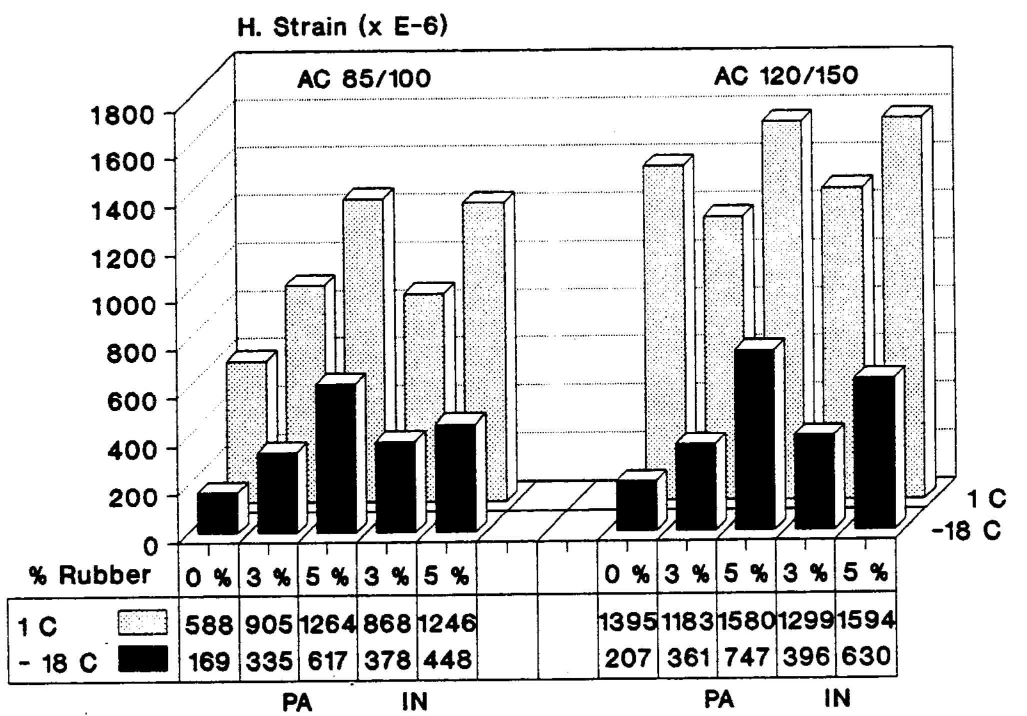


Figure 5.3. Comparison of Horizontal Strains at Cold Test Temperature.

The increased ability of a mixture to strain at cold temperatures can be taken as an indication of its increased resistance to thermal cracking. Therefore, the use of crumb rubber in asphalt concrete mixtures could be expected to reduce thermal cracking. The benefits of crumb rubber are increased at colder temperatures and stiffer neat asphalt cements.

Based upon these results, it is suggested that the testing protocol be altered so that the dissipation of stress build up can be more fully investigated. One possibility for changing the testing would be to use a much slower load so that any viscous behavior has a chance to fully develop at the colder test temperatures. Alternatively, the permanent deformation testing commonly used to evaluate rutting potential at warm temperatures could be adapted for cold temperature testing. This type of testing would allow the analysis of the individual components of viscous, elastic, and plastic behavior.

Resilient Modulus Test (Temperature Susceptibility)

Since there were three specimens in one set and the resilient modulus test was conducted at two locations (0 and 90°) per specimen, there were six resilient modulus values per test condition. These values are averaged and shown in Table 5.4 at the specified test temperatures. The complete test results for the resilient modulus test were listed in Appendix F.

Table 5.3 shows that there is little difference between either of the control (i.e., no rubber) mixtures. An increasing percentage of crumb rubber results in a corresponding decrease in modulus regardless of the type of crumb rubber. The modulus for the 85/100 penetration asphalt cement CRM asphalt concrete mixtures decreased from 20 to 40 percent for the 3 and 5 percent crumb rubber (either type), respectively, at the colder test temperatures. The reduction in mixture stiffness was 40 to 60 percent, respectively, at the warmer temperatures.

When the grade of binder was changed to the softer 120/150 pen asphalt cement, the moduli became dependent upon the type as well as the percentage of crumb rubber. At cold temperatures, the moduli of mixtures with passenger tire rubber decreased about 20 to 25 percent, regardless of the percentage of rubber; industrial tire rubber decreased the moduli from 35 to 60 percent for 3 and 5 percent crumb rubber, respectively. At the warmer temperatures, moduli decreased from 35 to 60 percent for 3 and 5 percent passenger tire rubber, respectively, and 65 to 80 percent for the industrial tire rubber.

The decreasing moduli values when crumb rubber is added to the mixtures are expected. As the rebound of the mixture is increased by the inclusion of rubber particles, more deformation can take place due to the compression of the rubber particles. This deformation however is mostly recoverable. Since the resilient modulus is calculated by dividing the applied stress by the recoverable deformation, when the recoverable deformation is increased, the modulus will decrease.

Table 5.4. Results of Resilient Modulus Test.

Asphalt Cement Grade	Type of Crumb Rubber	Percent of Pretreated Crumb Rubber %	Air Voids %	Resilient Modulus at Various Test Temperatures, MPa (ksi)			
				-18°C (0°F)	1°C (34°F)	25°C (77°F)	40°C (104°F)
85/100	None	None	4.8	6125 (888)	3715 (540)	2940 (426)	1381 (200)
	Passenger	3	7.5	4773 (692)	3073 (446)	2055 (298)	844 (123)
		5	8.9	3831 (556)	2699 (391)	1333 (193)	582 (85)
	Industrial	3	7.4	4549 (660)	2471 (358)	1890 (274)	728 (106)
		5	9.1	3584 (520)	1907 (277)	1047 (152)	433 (63)
120/150	None	None	4.2	6893 (1,000)	5366 (778)	2350 (341)	1355 (197)
	Passenger	3	7.2	5321 (772)	3875 (562)	1731 (251)	880 (128)
		5	8.5	5118 (742)	3052 (443)	1130 (164)	514 (75)
	Industrial	3	7.6	4482 (650)	2463 (357)	1273 (185)	461 (67)
		5	9.5	3392 (492)	1818 (264)	832 (121)	291 (42)

Figures 5.4 and 5.5 show the temperature relationships for these mixtures; a change in slope on these figures would indicate a change in temperature susceptibility. That is, if the slope becomes flatter, the temperature susceptibility of the mixture is decreased. These figures show that while there is a substantial decrease in moduli at any given temperature when crumb rubber is added to the mixture, there is little change in the slope of the lines. This would indicate that the presence of crumb rubber does not significantly affect the temperatures susceptibility of the mixture, but does reduce the mixture stiffness at any given temperature.

Increasing the percentage of crumb rubber also results in an increase in voids. Since the binder content was selected to obtain voids around 4 percent, this is surprising. This phenomena appears to be the result of minor fluctuations in the aggregate fraction stockpiles. As was seen in the compactibility study, only a minor change in gradation between Gradations A and B generally resulted in voids increased 2 to 4 percent. If this hypothesis is correct, these mixtures will be very difficult to control during construction as the gradation variations used in this portion of the study could be considered to be within the allowable target range for plant process control. The differences in air voids between the mixtures could also account for some of the reduction in moduli values seen in Table 5.4.

CONCLUSIONS

This portion of the research program yielded the following conclusions:

1. The addition of crumb rubber does not significantly affect the overall temperature susceptibility of the mixtures. It does, however, substantially decrease the mixture moduli at any given temperature. The decrease in moduli is accentuated as the percent of crumb rubber increases.
2. The addition of crumb rubber decreases the mixtures' potential for thermal cracking. This is accomplished by providing a mixture than can relieve stress build-up by its ability to strain. Changes in the testing protocol are needed to more fully investigate the ability of these mixtures to strain at low temperatures.

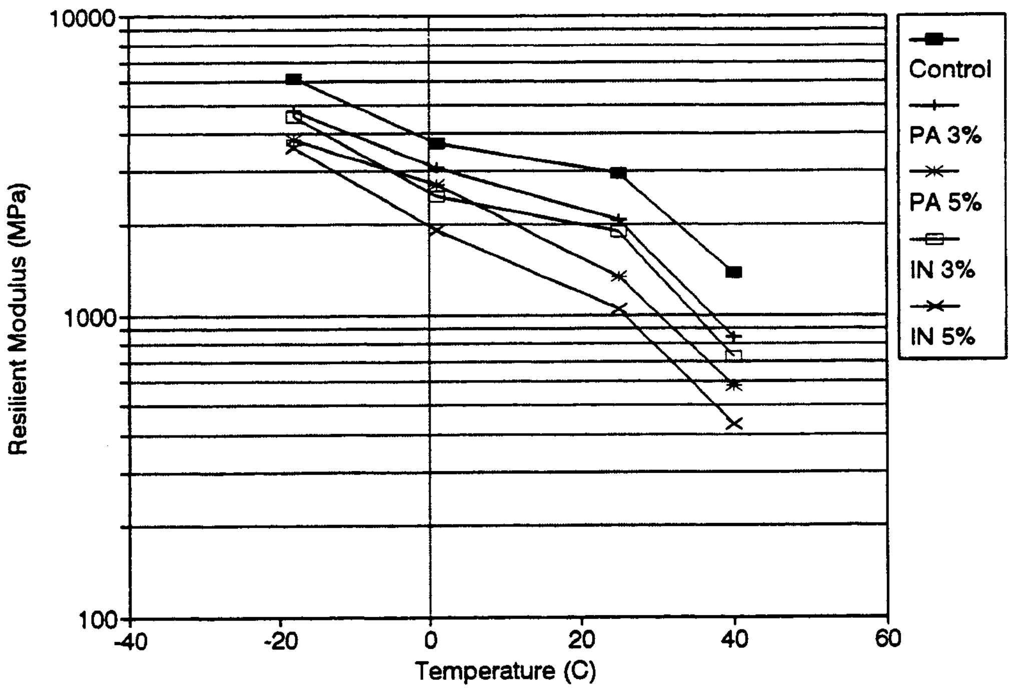


Figure 5.4. Temperature Susceptibility for 85/100 Pen Asphalt Cement.

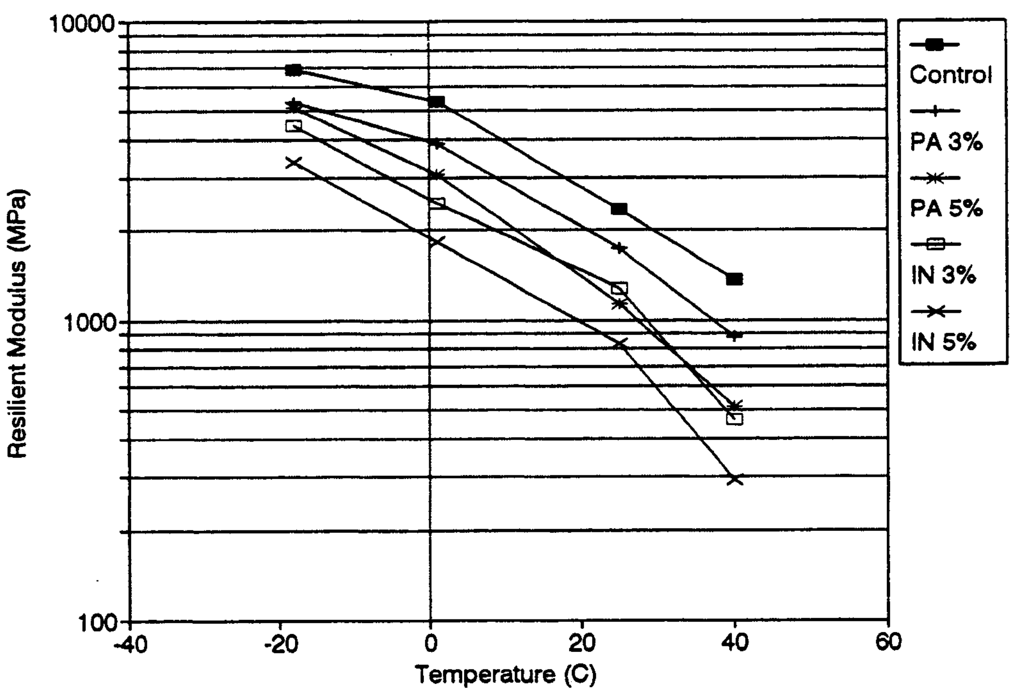


Figure 5.5. Temperature Susceptibility for 120/150 Pen Asphalt Cement.

CHAPTER SIX

PROJECT LOCATION

The project was located from just north of 152nd Ave. to County State Aid Highway (CSAH) 12 on Hennepin CSAH 13 near Rogers, Minnesota. The control section with the standard Mn/DOT Type 41 mixture (85/100 pen asphalt cement) was placed the full length of the southbound lane. The Type 41 with 6 percent rubber was placed in the northbound lane closest to 152 nd Ave. The next section placed in the northbound lane was the gap-graded mixture with 3 percent rubber. The last section in the northbound lane was the gap-graded mixture without rubber. Figure 6.1 shows the placement of the all test sections.

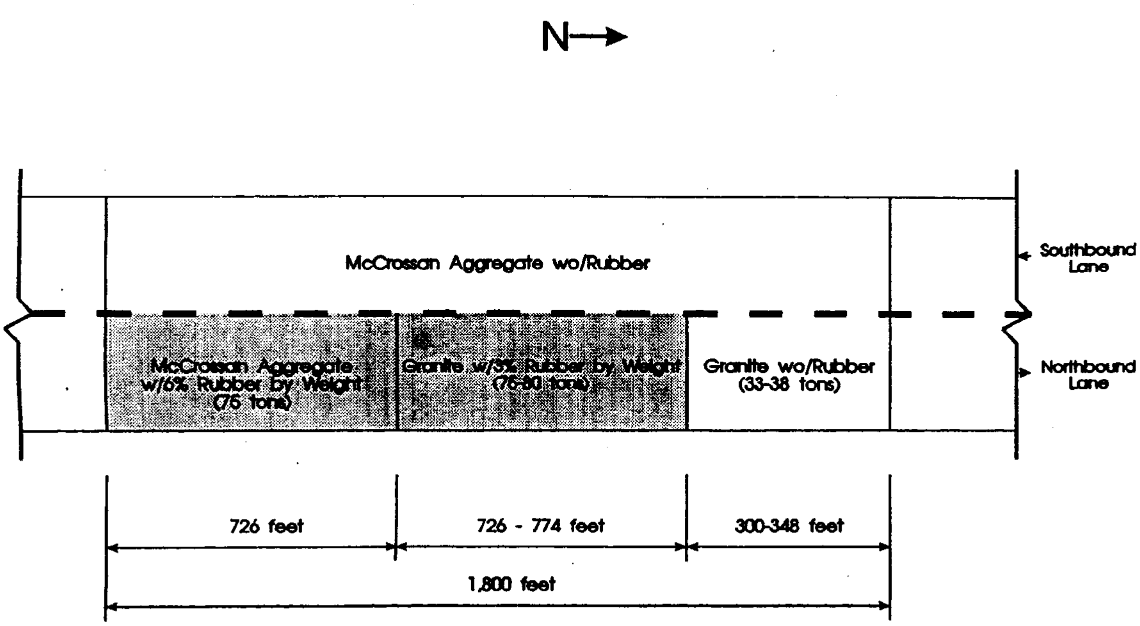


Figure 6.1. Layout of Test Sections.

HENNEPIN COUNTY FIELD TEST SECTIONS

OBJECTIVES

The objectives of placing these test sections in the fall of 1992 were to evaluate:

1. The performance of pretreated crumb rubber in both the preferred gap-graded aggregate gradation as well as in a typical dense-graded Mn/DOT 2331 Type 41 dense gradation.
2. Potential construction problems prior to the placement of test sections in Babbitt, Minnesota in the summer of 1993.

Previous laboratory research indicated that pretreating crumb rubber with 5 percent by weight tall oil pitch significantly reduced the interactions between the crumb rubber and the binder (Chapter Three). Therefore, this type and percent of pretreatment was selected for use in the field test sections.

MATERIALS

Asphalt Cement

Conclusions from the previous phases of the research program indicated that a softer grade of binder would interact better with the crumb rubber. Therefore, a 120/150 pen grade binder supplied by Koch Refinery was used instead of the 85/100 pen grade binder typically used in Hennepin County. The physical properties of the binder were not determined but would be expected to be similar to those used in the laboratory phases of the research.

The Type 41 standard Hennepin County mix (i.e., control mixture) supplied by C.S. McCrossan used their typical 85/100 pen asphalt cement.

Aggregates

Based upon information obtained during the previous phase of the research program, a gap-graded aggregate gradation was considered the most desirable. This type of gradation would provide more room for the crumb rubber between the aggregate particles and hopefully produce fewer voids. The literature review also indicated that gap-graded gradations perform best with high quality, crushed aggregates. However, these types of gradations and materials are not always available in Minnesota, therefore a typical Type 41 dense gradation was also selected.

The gap-graded crushed aggregate was a 100 percent crushed granite supplied by C.S. McCrossan, Maplegrove, Minnesota. The Type 41 gradation was comprised of partially crushed river gravel and limestone. A total of five gradations were used for mix designs (3 gap-graded, 2 Type 41). These gradations, including individual stockpile, rubber, and final combined gradations, are shown in Table 6.1. The percentage of each stockpile used to produce the laboratory gradations is shown in Table 6.2. Both the percent by weight of aggregate and the percent by volume are shown in this table.

Due to the time limitations, it was not possible to determine the specific gravities of the aggregates. The specific gravities for the aggregates were obtained from McCrossan at the time the mix designs were developed.

Rubber

Approximately 7 tons of passenger tire crumb rubber were pretreated with 5 percent tall oil pitch by weight of rubber and supplied to C.S. McCrossan's plant in Maple Grove, Minnesota by Whirl Air, Inc. in Babbitt, Minnesota. The passenger tire rubber was selected based upon its ability to have less of an impact on the mixture stiffness; it is also the most prevalent type of waste tire. The rubber was shipped in bulk in approximately 820 pound cardboard boxes. The gradation of the pretreated rubber is shown in Table 1.

Information on the tall oil pitch and the pretreatment of the rubber has been previously reported in Chapter Two.

Table 6.1. Individual Stockpile Gradations.

Sieve Size	Aggregate Stockpiles Cumulative Percent Passing					Target Combined Gradation
Gap-Graded Gradation Stockpiles						
Sieve Size	CA-50	FA-3	Meridian Dry Sand	CR-10 Rubber		Combined
3/4"	100	100	100			100
1/2"	77.6	99.5	99.8			95.8
3/8"	37.7	94.0	93.9			85.0
No. 4	5.1	27.5	62.3			44.2
No. 8	2.5	5.6	43.9	100		29.5
No. 16	1.9	2.8	31.6	54.3		18.7
No. 30	1.6	2.1	23.8	20.9		11.8
No. 50	1.3	1.7	17.6	7.4		7.7
No. 100	1.0	1.3	12.5	3.0		5.1
No.200	0.8	0.9	8.7	0.5		3.4
Type 41 Gradation Stockpiles						
Sieve Size	McCrossan Rock	McCrossan Fines	Burnsville Limestone	Additional Sand	CR-10 Rubber	Target Combined Gradation
3/4"	100	100	100	100		100
1/2"	43.9	99.4	89.2	99.6		95
3/8"	7.5	94.7	76.8	98.1		80
No. 4	1.8	70.0	54.0	90.4		66
No. 8	1.8	53.9	39.4	84.2	100	54
No. 16	1.8	40.4	30.7	73.5	54.3	35
No. 30	1.8	27.5	26.1	51.8	20.9	23
No. 50	1.7	15.8	22.3	18.9	7.4	13
No. 100	1.3	9.6	18.6	4.9	3.0	7
No. 200	0.9	6.6	15.3	2.0	0.5	5.0

Table 6.2 . Percentages of Stockpiles Used for Mix Design Gradations.

Mixture	Percentages by Weight of Stockpiles Used for Mix Design Gradations			
	Aggregate Stockpiles			
	CA-50	FA-3	Meridian Dry Sand	CR-10 Rubber
	Percentages by Weight of Stockpiles Used for Mix Design Gradations			
GR-0 (Granite Agg., 0% Rubber)	20	40	40	0
GR-3 (Granite Agg., 3% Rubber)	19	39	39	3
GR-5 (Granite Agg., 5% Rubber)	19	38	38	5
	Percentages by Volume of Stockpiles Used for Mix Design Gradations			
GR-0 (Granite Agg., 0% Rubber)	20	40	40	0
GR-3 (Granite Agg., 3% Rubber)	18	37	37	8
GR-5 (Granite Agg., 5% Rubber)	18	35	35	12
Dense-Graded Type 2341 (6% Rubber)	McCrossan Rock	McCrossan Fines	Burnsville Limestone	CR-10 Rubber
	Percentages by Weight of Stockpiles Used for Mix Design Gradations			
	12	63	8	17
	Percentages by Volume of Stockpiles Used for Mix Design Gradations			
	14	72	8	6

SAMPLE PREPARATION AND TESTING PROGRAM

Mix design samples were compacted and tested as described in the previous chapters. All samples used in research testing were compacted with 20 instead of 50 blows/side. This was so that the voids content would be within the anticipated field void content range (i.e., 6 to 8 percent). The testing program included an assessment of temperature susceptibility as described in Chapter Five. Instead of an assessment of low temperature behavior, an evaluation of moisture sensitivity was added to the testing program. This substitution was made after field observations during construction.

Moisture Sensitivity

The ASTM D4867 test method for determining the moisture sensitivity of asphalt concrete mixtures was used; the optional freeze/thaw procedure was included in the sample conditioning. A set of six samples was prepared for each gradation. Three samples from each set of six were taken to determine the original unconditional resilient modulus and indirect tensile strength. The remaining samples were vacuum saturated to between 55 to 80 percent, wrapped and frozen at -18°C (0°F) for 15 hours (minimum), then unwrapped and thawed in a 40°C (140°F) water bath for 24 hours. The samples were then moved to a 25°C (77°F) water bath for 2 hours to be brought to the testing temperature. The resilient moduli and indirect tensile strengths were then determined.

The resilient modulus was determined as described in the preceding section. The tensile strength was determined with a loading rate of 50 mm/min (2 in/min). Moisture sensitivity was expressed as a ratio of the wet to dry strengths. The resilient moduli and indirect tensile strengths, both before and after conditioning, the ratios, and the percent saturations achieved were reported.

PRE-CONSTRUCTION TESTING

Mix Designs

Mix designs for the test sections, with the exception of the Type 41 control (i.e., no rubber) were supplied by the University of Minnesota. A mix design previously completed by C.S. McCrossan and approved by Hennepin County was used for the Type 41 control. A conventional 50 blow/side Marshall mix design with rotating base and 1° bevel headed hammer was used for all mix designs, regardless of the laboratory providing the designs.

Table 6.3 shows all of the available data for the mix designs. This table shows a total of 6 mix designs (5 mix designs by the University, 1 by C.S. McCrossan). It can be seen that for the gap-graded mixtures, the Marshall stability decreases with increasing percentage of rubber; air voids, and flow increase with increasing percentages of rubber. The Type 41 shows

Table 6.3. Mix Design Results (50 Blows/Side).

Asphalt Cement Content (Total Weight of Mix)	Unit Weight (pcf)	Marshall Stability (lb.)	Flow (0.01 In.)	Air Voids (%)	VMA (%)
GR - 0 (Opt. AC 5.9% by Total Wt. of Mix)					
4.76	146.3	2071	10	6.0	14.75
5.21	145.7	1906	11	6.1	15.51
5.66	147.0	1864	10	4.4	15.22
6.10	146.8	1797	11	3.6	15.66
6.54	149.9	1765	11	1.4	14.32
GR - 3 (Opt AC 5.7% by Total Wt. of Mix)					
5.07	138.9	1355	12	7.7	19.46
5.50	139.0	1412	17	6.0	19.82
5.94	132.9	657	23	10.1	23.67
6.36	135.5	701	20	8.0	22.51
6.79	137.2	862	19	7.0	22.14
GR - 5 (Opt. AC >6.7% by Total Wt. of Mix)					
4.98	130.7	661	14	10.9	24.23
5.41	129.7	740	16	11.8	25.13
5.83	130.3	723	18	10.6	25.16
6.25	135.7	903	13	6.3	22.42
6.67	136.5	981	15	6.0	22.51
41-Standard (Opt. AC 5.8% by Total Wt. of Mix)					
Data not obtained from Hennepin County Records					
41-3R (Opt. AC 6.0% by Total Wt. of Mix)					
4.76	136.4	908	11	7.6	---
5.21	135.8	939	17	8.1	---
5.66	135.0	853	18	7.1	---
6.10	142.4	1286	16	2.7	---
6.54	139.6	1181	18	2.5	---
41 - R (Opt. AC 5.8% by Total Wt. of Mix)					
5.88	137.6	1382	19	3.5	15.98
6.46	134.5	1169	19	2.8	18.3
6.95	139.8	1192	18	---	15.48
7.49	137.1	1129	22	1.7	17.48
8.02	138.7	1177	22	0	16.88

* In mix design 41-R, the BSG of Agg. is assumed to be 2.500.
--- Indicates that no information is available

a slight increase in stability and flow, and a decrease in air voids with an increasing percentage of rubber. Based on this information, three of the five University of Minnesota mix designs were selected for the field test sections: gap-graded with no rubber (GR-0), gap-graded with 3 percent rubber (GR-3), and the Type 41 with 6 percent rubber (41-R).

Laboratory notes indicate that all mixtures with any percentage of rubber had a characteristic dome on the top of the sample. It was also noted that the Type 41-R samples looked dry; there was no "shine" that is characteristic of conventional mixtures at higher than optimum asphalt content.

Temperature Susceptibility

Table 6.4 shows that both the gap-graded with 3 percent rubber and the Type 41 with 6 percent rubber have similar temperature susceptibility. Comparing the gap-graded with and without rubber mixtures, a substantial decrease (approximately 70 percent) in moduli values for all temperatures can be seen when rubber was added; this is expected and is similar to those results reported in Chapter Five. Figure 6.2 shows that there is no change in the temperature susceptibility for any of the mixtures, even though there is a substantial decrease in moduli for any given temperature.

Table 6.4. Temperature Susceptibility.

Frequency (Hz)	Resilient Modulus, MPa (ksi) Mix Design Samples		
	34	77	104
GR - 0			
0.33	4,548 (674)	1,846 (275)	1,007 (146)
0.5	4,662 (676)	1,869 (271)	931 (135)
1.0	4,679 (678)	1,855 (269)	883 (128)
GR - 3			
0.33	1,538 (223)	618 (89)	395 (57)
0.5	1,545 (224)	600 (87)	359 (52)
1.0	1,469 (213)	586 (85)	337 (49)
41 - R			
0.33	1,566 (227)	600 (87)	338 (49)
0.5	1,620 (235)	620 (90)	331 (48)
1.0	1,588 (230)	628 (91)	338 (49)

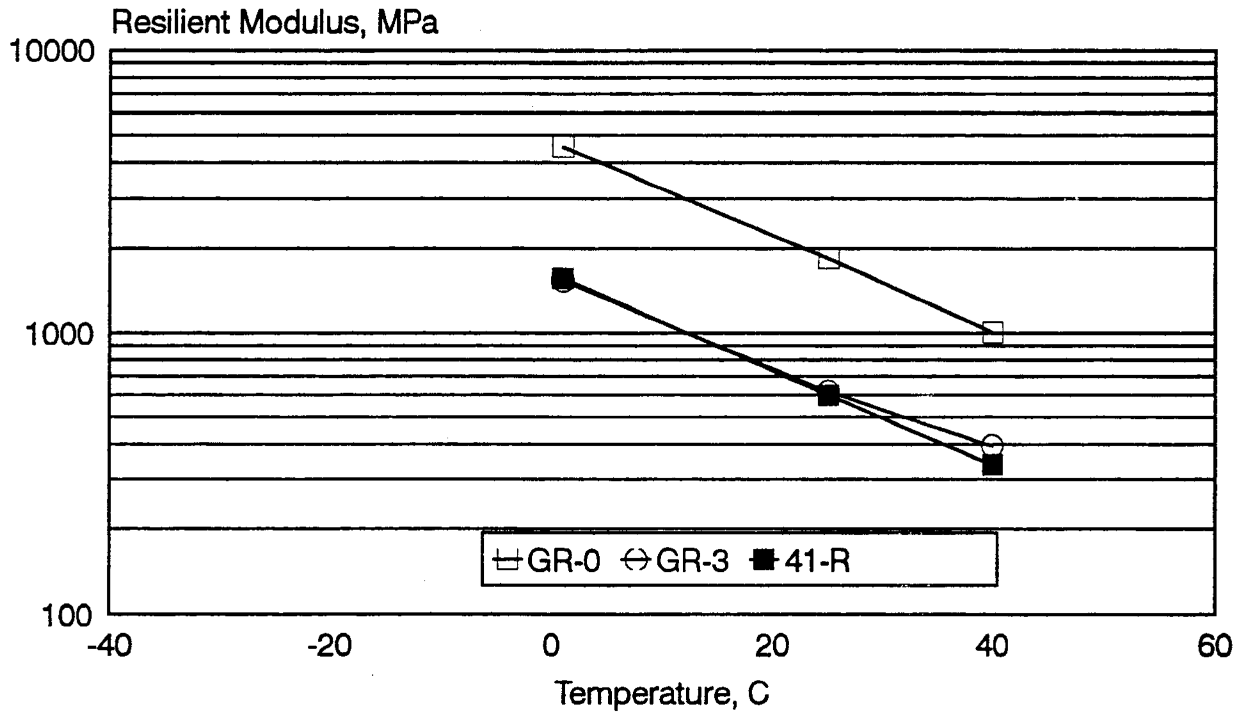


Figure 6.2. Temperature Susceptibility of Pre-Construction Mixtures for Hennepin County Test Sections.

Moisture Sensitivity

While this data has been included in the laboratory testing section, this testing sequence was actually added after observations of apparent raveling were noted in the field sections. This testing was originally not thought to be important as nothing in the literature review indicated the use of crumb rubber in mixtures would significantly increase moisture sensitivity of a cally non-stripping mixture.

Table 6.5 shows the results of this additional testing program. It can be seen that both mixtures containing rubber had similar resilient moduli and tensile strengths, but were significantly lower than gap-graded control mixture. However, there is a greater tendency for moisture damage for mixtures with crumb rubber. This increased damage is seen in a decrease in the retained stiffness (i.e., resilient modulus ratio); the gap-graded control mixture had a modulus ratio of 95 percent with the crumb rubber mixtures, regardless of gradation or percentage of rubber, had ratios around 50 percent. Little difference is seen in the ratios for the tensile strengths. However, the conditioned tensile strengths are so low as to indicate that the samples were barely testable. This in itself would indicate that these mixtures could be very sensitive to moisture damage.

Table 6.5. Moisture Sensitivity (Mix Design Samples).

	Resilient Modulus, 25°C (77°F) MPa (ksi)			Tensile Strength, 25°C (77°F) kPa (psi)		
	Dry	Wet	Ratio (%)	Dry	Wet	Ratio (%)
GR-0	1,897 (275)	1,786 (259)	94	1,152 (167)	579 (84)	50
	1,870 (271)	1,772 (257)	95	966 (140)	483 (70)	50
	1,855 (269)	1,800 (261)	97	1,021 (148)	517 (75)	51
Average	1,879 (272)	1,786 (259)	95	1,042 (152)	524 (76)	50
GR-3	613 (89)	---	---	607 (88)	---	---
	600 (87)	310 (45)	52	---	242 (35)	40
	586 (85)	366 (53)	62	---	241 (35)	40
Average	600 (87)	338 (49)	57	607 (88)	241 (35)	40
41-R	600 (87)	270 (39)	45	193 (28)	90 (13)	46
	620 (90)	276 (40)	44	213 (31)	97 (14)	46
	628 (91)	283 (41)	45	179 (26)	83 (12)	46
Average	614 (89)	276 (40)	45	193 (28)	90 (13)	46

CONSTRUCTION

Plant Construction Notes

The boxes of rubber were cut open and dumped into a loader bucket with a fork lift. The rubber initially retained the box form when the cardboard was cut from one side, but easily crumbled when touched or moved. The rubber was then loaded into the RAP hopper of the plant and metered into the heated aggregate elevator by means of conveyor belt equipped with a belt scale. The rubber flowed easily from the hopper onto the belt and appeared to be evenly distributed on the belt. Some pea-sized lumps of what appeared to be excess tall oil pitch and tackified rubber were noted.

Plant temperatures were increased about 10 to 15°F over plant temperatures typically used for unmodified mixtures with the 120/150 pen asphalt cement.

Highway Construction Notes

All mixtures were easily placed with no changes required in normal laydown procedures. A steel wheel roller was used for compaction of all sections; breakdown consisted of two static passes (one pass=up and back) followed by at least 2 additional passes with the vibrators on. Finish rolling used another single static pass.

Weather conditions during construction were good: clear with light winds, and temperatures around 25°C (77°F).

Type 41

The Type 41 mixture with rubber did not appear to compact well with or without vibration. There was a small patch of corrugation-type damage at the start of the section after the final vibratory pass although this type of damage was not noted elsewhere in the section. Typical mat temperatures during compaction were between 250 and 260°F; this mat appeared to retain the heat much longer than would be expected of an unmodified mixture.

The finished surface was spongy; large aggregate on the surface could be pushed down with a pencil tip and the aggregate would rebound when released. The surface remained very tacky and mix could be picked up on the bottom of rubber soled shoes. These problems appeared to disappear when the mat had cooled to around 140°F. The finished mat had a dull black appearance; the mixture looked dry and scuffed easily under traffic.

Gap-Graded With 3 Percent Rubber

No problems were noted during construction. Mat temperatures and compaction sequences were similar to those used to construct the Type 41 with rubber. Two small patches of excess asphalt and/or rubber formed in this section with no obvious explanation. The finished surface had an open-graded appearance with a dull black coloring.

Gap-Graded Without Rubber

This mixture had severe drain down problems in the haul truck. Otherwise, construction proceeded as described above. Mat temperatures were much hotter (over 275°F) than the other mats. Information obtained from the plant indicates that the mix temperature of this unmodified mixture the same as for the crumb rubber modified mixtures, that is, at least 15°F higher than would typically be used for this grade of asphalt cement. The elevated temperature appears to have occurred due to a misunderstanding: the plant operator applied the requirement for an elevated mix temperature for modified mixtures to both crumb rubber modified and *gradation* modified. Both the drain down problem and the high mat temperatures are most likely a result of the elevated mix temperatures; no similar problems were noted during the mix design phase. The finished surface also had an open-graded appearance but with a shiny black coloring.

POST CONSTRUCTION

An initial inspection of the new test sections October 27, 1992 by D. Newcomb and M. Stroup-Gardiner of the University of Minnesota noted that the control Type 41 mix had a smooth, tight surface while the Type 41 with 6 percent rubber looked dry with signs of raveling.

Both the gap-graded mixtures looked good with the only differences noticeable between the sections being the color of the pavement. Traffic noise was noticeably reduced on both of the rubber sections.

A second evaluation of the test sections in late November, 1992 showed severe raveling in the Type 41 with 6 percent crumb rubber test section. This test section was subsequently milled off prior to January, 1993. The gap graded mixture with 3 percent crumb rubber also showed signs of early raveling; this section was milled off during the summer of 1993.

Limited quantities of the field mixtures were supplied to the University of Minnesota laboratory by Hennepin County. This material was used to fabricate compacted samples and compare mixture properties obtained during the mix design phase with the properties of the construction mixtures. Also included are data from the standard acceptance testing completed by Hennepin County. This information is reported below.

Laboratory Testing

Table 6.6 presents a comparison of mix design information and data reported by Hennepin County for acceptance testing. Both gap-graded mixtures show comparable results for air voids and stabilities. There was some difference noted in the maximum specific gravities which was most likely attributable to the difficulty in testing crumb rubber modified mixtures.

There was a large difference in all of the properties reported for the Type 41 crumb rubber modified mixtures. While the mix design results showed values comparable to those reported by Hennepin County for the unmodified Type 41, the acceptance testing results showed exceptionally poor results for the Type 41 crumb rubber modified mixtures. This would indicate a problem occurred in the stockpile sampling for the mix designs, or that laboratory practices of adding the rubber result in mixtures dissimilar to those produced during construction.

One difference between the laboratory and field-produced mixtures had to do with the method of adding the rubber. During the laboratory mix design process, the rubber was added after the asphalt cement and aggregates had been mixed; at this time it was assumed that the rubber would be supplied in 50 pound bags and manually added at the pugmill. However, the rubber was delivered in bulk and added from the RAP hopper to the heated aggregate prior to mixing with the asphalt cement. This difference in adding the rubber could result in the different mixture properties. A small experiment was designed to investigate different methods of adding crumb rubber on mixture properties.

Table 6.6. Comparison of Mix Design and Acceptance Testing Test Results

Test	Mix Design			Acceptance Testing			
	41-R	GR-0[1]	GR-3[1]	41 Control	41-R	GR-0	GR-3
Air Voids, %	3.5	4.0	6.0	4.4	18	4.5	8.3
Marshall Stability, kN (lb)	6.15 (1382)	8.01 (1800)	5.34 (1200)	5.25 (1179)	1.57 (353)	6.35 (1427)	5.25 (1182)
Theoretical Maximum Specific Gravity	2.286	2.450	2.369	2.491	2.410	2.530	2.455

1: Values estimated from mix design data.

Investigation of Methods of Adding Crumb Rubber

A small laboratory study was conducted to determine the effect of adding the rubber to 1) hot aggregate prior to the addition of the asphalt cement (simulating addition of rubber from the RAP hopper during construction) , and 2) after the aggregate and asphalt cement have been mixed (simulating addition of bagged rubber to the pugmill). The laboratory procedures for these two methods of adding the rubber were:

1. *RAP*: Aggregate was preheated to 375°F overnight, then added to the mixing bowl. The rubber was added to the heated aggregate, mixed, and then the asphalt cement was added to the bowl. The sample was then mixed as usual.
2. *Pug*: Aggregate was preheated to 300°F overnight, added to the mixing bowl along with the asphalt cement. The materials were mixed; the rubber was added during the mixing but after the aggregates were coated with asphalt cement.

Temperature Susceptibility

Table 6.7 shows the influence of temperature on resilient moduli for samples prepared during the original mix design phase, and samples prepared to simulate both RAP and pugmill addition of rubber. There was a substantial difference between the mix design pug-simulated and the pug-simulated samples prepared about 2 months after the mix design samples. This was most likely a function of the changes in the pretreated rubber during storage. There was little difference between the either method of adding the rubber for samples prepared with the stored pretreated rubber. This would indicate that the changes in the rubber properties during storage have a larger influence on mixture properties than the method of adding the rubber.

Table 6.8 shows the moisture conditioning results. This table shows that there was a uniform increase in the unconditioned resilient moduli values for the RAP and pug samples compared to the original mix design samples. However, tensile strengths of the RAP and pug samples were slightly lower than the original mix design samples. The only major difference that can be seen between any of the samples is in the after conditioned tensile strengths: the pug samples do not lose any tensile strength after conditioning while both the RAP and mix design samples do lose strength. Again this difference could be a function of the changes in the properties of the pretreated rubber over time.

In general, there was little difference in the mixture properties obtained by either method of adding the rubber in the laboratory. Neither the temperature susceptibility of the mixture nor, in general, the moisture sensitivity was greatly different between the mixtures.

Since there appeared to be some effect from the length of time between pretreatment and use of crumb rubber, the Brookfield viscosities were also Table 6.9 shows that the properties of the pretreated rubber changed substantially with the increased storage time. While the Brookfield viscosity of any combination of asphalt cement and rubber is substantially increased when compared to the neat binder viscosity, there was also a noticeable reduction in the viscosity with increased storage time. The decrease in the viscosity is assumed to indicate a reduced interaction between the asphalt cement and the rubber. This storage time dependency of the asphalt-rubber interactions could be one of the reasons for the differences in test results between the mix design and acceptance testing data.

Table 6.7. Resilient Modulus Test Results.

Mixture	Sample No.	Resilient Modulus, MPa (ksi)		
		34°F	77°F	104°F
Mix Design Data (GR-3) Pug-Simulated Mixing	Average	1,538 (223)	614 (89)	8.3 (57)
RAP-Simulated Mixing	1	2,248 (326)	779 (133)	559 (81)
	2	2,662 (386)	1,275 (185)	586 (85)
	3	2,572 (373)	1,137 (165)	497 (72)
	Average	2,496 (362)	1,110 (161)	554 (79)
Pug-Simulated Mixing	1	2,587 (375)	1,069 (155)	517 (75)
	2	2,587 (375)	1,089 (158)	358 (52)
	3	2,606 (378)	1,055 (153)	538 (78)
	Average	2,593 (376)	1,068 (155)	468 (68)

Table 6.8 . Moisture Sensitivity Test Results.

Mixture	Sample No.	Resilient Modulus, MPa (ksi)			Tensile Strength, kPa (psi)		
		77°F Dry	77°F Wet	Ratio (%)	77°F Dry	77°F Wet	Ratio (%)
Mix Design Data Pug-Simulated Mixing	1	600 (87)	340 (49)	57	607 (88)	241 (35)	40
RAP-Simulated Mixing	1	917 (133)	---	---	476 (69)	---	---
	2	1,276 (185)	469 (68)	37	---	310 (45)	65
	3	1,139 (165)	345 (50)	30	---	248 (36)	52
	Average	1,110 (161)	407 (59)	34	476 (69)	283 (41)	59
Pug-Simulated Mixing	1	1,069 (155)	---	---	435 (63)	---	---
	2	1,090 (158)	517 (75)	48	---	428 (62)	100
	3	1,055 (153)	517 (75)	49	---	462 (67)	106
	Average	1,069 (155)	517 (75)	49	434 (63)	449 (65)	103

Note: ---- indicates no data available.

Table 6.9. Asphalt-Rubber Interactions for Manufacturer Pretreated Rubber.

Test		Percent Rubber Added to Neat 120/150 Pen AC (Rubber Pre-Treated by Manufacturer)		
		None	20% Rubber (Approx. 1 month after pretreat.)	20% (Approx. 3.5 months after pre-treat.)
3 Hr. Brookfield Viscosity (Poise)	10 RPM	0.71	36.6	20.2
	20 RPM	0.69	27.7	16.6
	50 RPM	0.75	19.6	13.4
	100 RPM	0.74	15.6	11.7

CONCLUSIONS

Conclusions from this effort are:

1. Resilient moduli for either mixture containing crumb rubber was reduced to approximately 70 percent of the unmodified gap-graded mixtures over a wide range of temperatures (no data were obtained for the control Type 41 mixture). This type of decrease is expected when deformable mixtures are tested; the resilient modulus test does not measure permanent deformation, only elastic deformation. Both the gap-graded and Type 41 mixtures had similar moduli.
2. After noting problems with excessive ravelling in the test sections, the moisture sensitivity of the materials used for the mix design work was evaluated. This testing showed that moistures sensitivity (i.e., resilient modulus and tensile strength ratios) increased for both mixtures with crumb rubber. These mixtures also have very low

initial resilient moduli and tensile strengths, which appears to have compounded the problem with the increased moisture sensitivity.

3. Mix designs did a good job of estimating the air voids and stability of the gap-graded mixtures. However, for some reason the laboratory mixed Type 41-R did not come close to matching the properties obtained from field mixed samples. Possible reasons for this discrepancy include 1) differences between the aggregates used for the mix design and construction, 2) sensitivity of dense-graded mixtures with crumb rubber to small gradation changes, 3) differences in methods of adding the crumb rubber in the laboratory and field, and 4) different storage times of pretreated rubber.
4. The properties of the pretreated rubber changed with storage time. The asphalt-rubber interactions, as measured by determining the Brookfield viscosity, were substantially decreased with increasing storage time.
5. Methods of adding the crumb rubber to the mixture had little effect on mixture properties with the exception of the moisture conditioned tensile strengths.

RECOMMENDATIONS

Pretreating the crumb rubber with tall oil pitch resulted in a significant reduction in the interaction between the rubber and the asphalt cement. Originally, this was thought to be desirable from the standpoint of reducing the rubber's demand for the light fractions of the asphalt cement. However, based upon the results of the field sections, this reduction in interaction also appeared to result in a reduction of the adhesive bond between the rubber and the asphalt cement. This in turn appeared to lead to excessive raveling of the crumb rubber mixture.

Based upon these observations, a method of pretreating the rubber that both satisfies the rubber's demand for light fractions and improves the adhesiveness of the asphalt-rubber interface would be desirable. The next phase of the research proceeded in this direction.

CHAPTER SEVEN

PROJECT LOCATION

The project, constructed in early September, 1993, is located on County State Aid Highway (CSAH) 112, also known as Central Boulevard, from Babbitt Road to South Drive, in the city of Babbitt, Minnesota in St. Louis County. Test sections consisted of two control sections, one at either end of the project, and at total of four CRM mixture test sections. Two sections have 1 percent of pretreated rubber in the 50-mm (2-in) wear course and unmodified control mix in the bottom 50 mm (2 in) of bituminous base and 50-mm (2-in) of binder course. The last two sections have 1 percent of either treated or untreated crumb rubber in all bituminous mixtures. The general locations and pavement cross sections of the test sections are shown in Figures 7.1 and 7.2, respectively. Table 7.1 describes the test section variables and stationing.

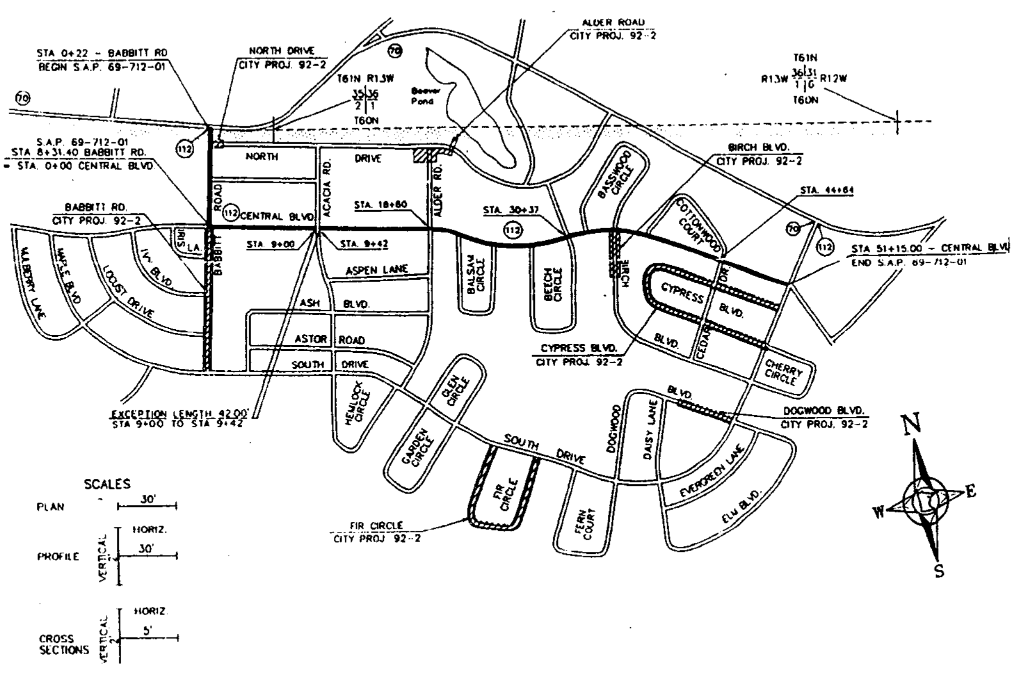


Figure 7.1. Project Location and Test Section Cross Sections.

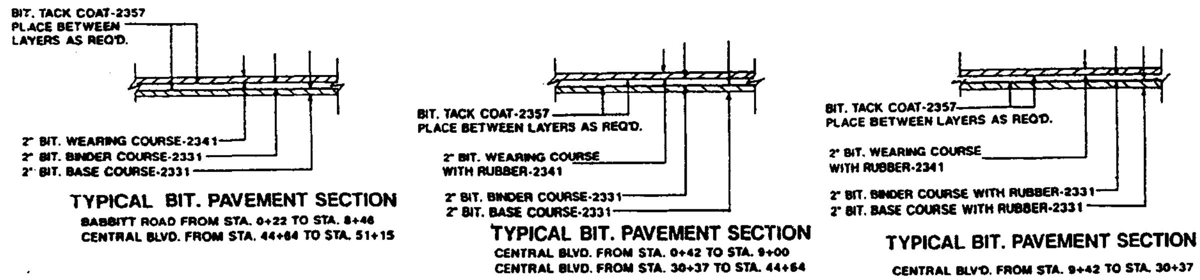


Figure 7.2. Typical Cross Sections.

Table 7.1. Description of Variables and Locations of Test Sections.

Road	Stations	Variable
Babbitt Road	0 + 22 to 8 + 46 (CSAH 70 to Central Blvd.)	Control
Central Blvd.	44 + 66 to 51 + 5 (Cedar Dr. to South Dr.)	Control
Central Blvd. (TS1)	0 + 20 to 9 + 00 (Babbit Rd. t Acacia Rd.)	CRM modified wear course only 1% Pre-treated (10% Hydrolene 90)
Central Blvd. (TS2)	9 + 45 to 17 + 50 (Acacia Rd. to All State Insurance Bldg.)	CRM modified wear, all lifts 1% Pre-treated
Central Blvd. (TS3)	17 + 50 to 21 + 00 (All State Insurance Bldg. to W. Balsam Circle)	Control, wear course CRM modified base, binder 1% Pre-Treated (10% Hydrolene 90)
Central Blvd. (TS4)	21 + 00 to 34 + 50 (W. Balsam Circle to Birch Blvd.)	CRM modified, all lifts 1% Untreated
Central Blvd. (TS5)	34 + 50 to 51 + 50 (Birch Blvd. to South Drive)	CRM modified, wear course only 1% Untreated

OBJECTIVE

The objectives of this last field project were to:

1. Compare properties of mixtures prepared during mix design to those of actual construction materials.
2. Evaluate the construction process associated with the construction of these sections.

SCOPE

A conventional Mn/DOT Type 31 gradation was used for both the control base and binder courses; a Type 41 was used for the control wear course. The same base and binder courses were used under the CRM (treated or untreated) wear course. All CRM mixtures were prepared with one gap-graded gradation.

Based on the results from the Hennepin County field test sections, the pretreatment was changed from the tall oil pitch to a light oil petroleum product. This pretreatment was added at a level of 10 percent by weight of rubber.

MATERIAL PROPERTIES

Asphalt Cement

The 120/150 penetration grade asphalt cement used for this project was obtained from Murphy Asphalt, located in northern Minnesota. The properties of this asphalt cement were similar to those of the Koch 120/150 penetration grade asphalt cement used in the previous research programs.

Aggregates

Two stockpiles of aggregates were submitted to the University of Minnesota by the paving contractor (Glacier Paving, Babbit, Minnesota). The gradations and physical properties of these materials are shown in Table 7.2. Gradation information was also obtained from the Mn/DOT Duluth laboratory as a double check on the stockpile gradations. The coarse gradations agreed very well but there was a substantial difference in the finer aggregate gradation. Since this difference in the stockpile gradations would lead to substantial differences in the final combined gradations the final blending percentages were based on a final sieve analysis performed by the Duluth Mn/DOT laboratory just prior to construction. These final stockpile gradations are also shown in Table 7.2. Figure 7.3 shows the mix design gradation and resulting gradations for both a 35/65 and 45/55 blend of coarse/fine aggregate. Based on these results, a field blend of 40/60 was selected as the gradation to be used for the CRM mixtures as it provided a gradation closest to the mix design gradation.

Table 7.2. Aggregate Gradations.

Sieve Size	University of Minnesota Stockpiles			Mn/DOT Duluth Stockpiles	
	Cumulative Percent Passing, %				
	19 mm (3/4 in) Minus	12.5 (1/2 in) Minus	Combined Target Gradation[1]	19 mm (3/4 in) Minus	12.5 (1/2 in) Minus
19 mm (3/4 in)	100		100	100	
15.5 mm (5/8 in.)	---	---	---	91.5	
12.5 mm, (1/2-in.)	49.2	100	75.1	31.2	100
9.5 mm (3/8-in)	14.2	96.8	56.4	4.4	88.0
4.75 mm (No. 4)	8.5	72.8	41.6	3.1	76.6
2.00 mm (No. 8)	8.5	56.3	33.3	---	---
1.8 mm (No. 10)	---	---	---	2.6	59.4
1.18 mm (No. 16)	8.4	42.7	26.1	---	---
1.0 mm (No. 20)	---	---	---	---	---
0.60 mm (No. 30)	8.2	31.6	20.1	---	---
0.75 mm (No. 40)				1.9	30.4
0.30 mm (No. 50)	7.1	20.3	13.7	---	---
0.20 (No. 80)	---	---	---	---	---
0.15 mm (No. 100)	4.8	11.8	8.3	---	---
0.075 mm (No.200)	2.8	6.7	4.7	0.5	6.5

1: Target gradation includes 1 percent of the crumb rubber. Rubber is substituted by volume; this amounts to a 1:3 rubber to aggregate weight substitution.

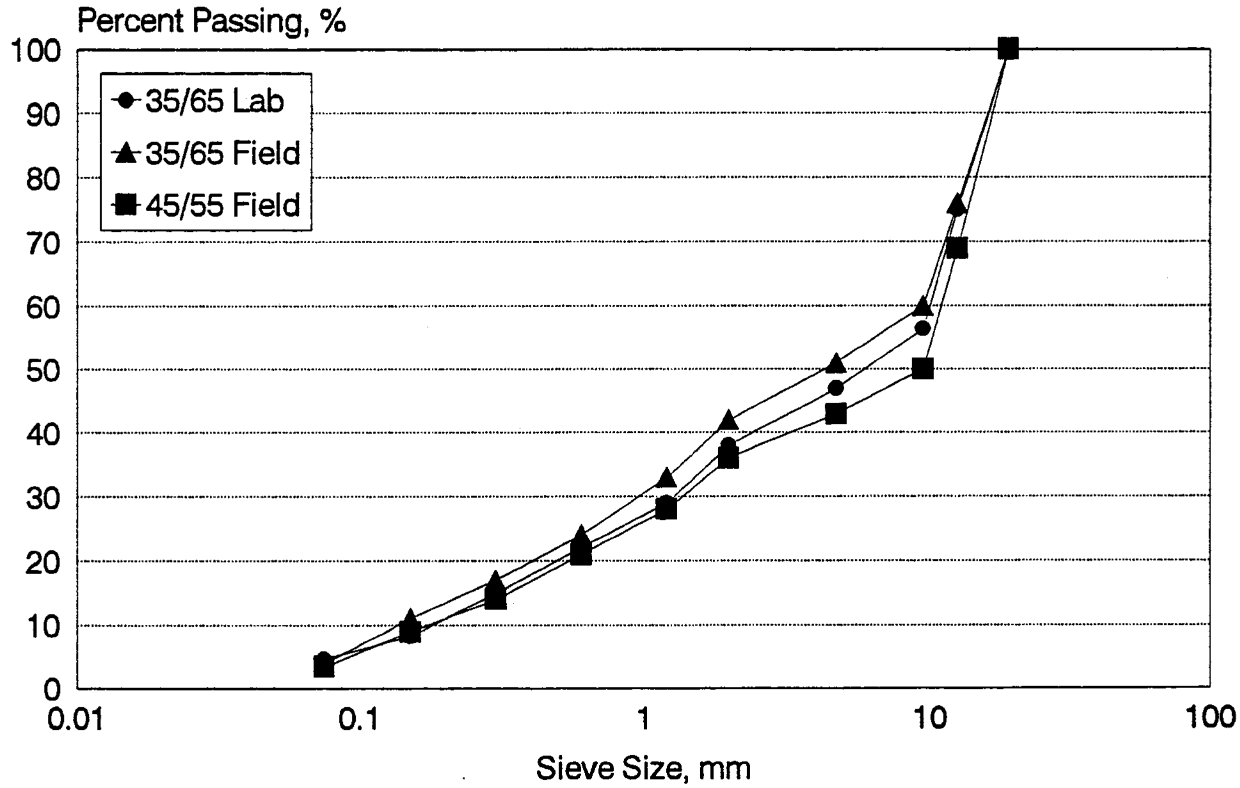


Figure 7.3. Gradations for Mix Design and Field Blends.

Rubber

The same passenger tire rubber gradation used for all previous research was used in this study as well.

Pretreatement

Based on the results from Chapter Three and the Hennepin County field test sections (Chapter Six), a second type of crumb rubber pretreatment was sought. The product finally selected was Hydrolene 90 produced by Sun Oil and Marketing Company, Philadelphia, Pennsylvania. This product is a heavy paraffinic distillate solvent extract commonly used in the manufacture of tire rubber (i.e., the extender oil). Also, since it is a petroleum based product, it should be more compatible with the asphalt cement. Table 7.3 shows the typical physical and chemical properties. Both the low molecular weight and the high percentage of total aromatics indicate this product to be a good pretreatment for the crumb rubber.

Table 7.3. Physical and Chemical Properties of Hydrolene 90.

Property	Applicable ASTM Method	Values
Physical Properties		
Viscosities: 38°C (100°F), SUS 99°C (210°F), SUS	 D2161 D2161	 7,000 123
Specific Gravity	D1250	1.000
Molecular Weight	D2502	395
Pour Point, °C (°F)	D97	13 (55)
Flash Point°C (°F)	D92	445
Chemical Properties		
Clay-Gel, Wt. 5% Asphaltenes Polar Compounds Aromatics Total Aromatics Saturates	D2007	 0.1 13.5 70.9 84.4 15.5

SAMPLE PREPARATION AND TESTING PROGRAM

The mix design samples were prepared as previously described. A 50 blow/side Marshall mix design was used to determine the optimum asphalt cement content.

All samples used for research testing were prepared with Marshall compaction with 20 blows per side instead of 50 blows/side. This was done to increase the level of air voids to within the anticipated field void range (typically 6 to 8 percent). Testing programs for establishing temperature susceptibility, moisture sensitivity (as described in Chapter Six), and low temperature behavior were completed for both the mix design materials and the behind the paver materials obtained during construction. Permanent deformation characteristics were determined only for the behind the paver materials.

Low Temperature Behavior

This test was conducted as described in Chapter Five, except the constant rate of deformation was slowed to 0.25 mm/min (0.01 in/min).

Permanent Deformation Characteristics

Sample Preparation

A modified Marshall hammer (10 kg (22 lb)) was used to prepare 100 mm (4 in) diameter by 200 mm (8 in) high cylinders for testing. The mixture was placed in the mold in a series of three lifts; each lift was compacted prior to adding the next. Each lift was compacted with different number of blows so that uniform air voids would be obtained throughout the sample. The first (i.e., bottom) lift was compacted with 30 blows, the second and third (i.e., middle and top) lifts were compacted with 25 and 18 blows, respectively. Unlike the conventional Marshall compaction method, the both sides of the sample were not subjected to the compactive effort.

Testing

The test method consisted of a preconditioning load (2 kPa (30 psi)) applied to the sample for 5 minutes. The load was then removed and the sample allowed to recover for 2 minutes. The load was then reapplied for 1 hour and the axial deformation was measured over the center one third of the sample. The recoverable deformation was measured for 15 minutes after the load was removed. No confining pressure was used. Samples were tested at 40 °C (104°F).

PRECONSTRUCTION TESTING

Mix Designs

Table 7.4 shows the results of three mix designs that were completed for this project. Two aggregate gradations were used: 1) a 35/65 blend, and 2) a 50/50 blend of fine and coarse aggregates. The 35/65 blend was selected for use in the field project as this combination produce acceptable mix design properties and would not be as coarse in texture as the 50/50 blend. The optimum asphalt content was selected as 6.5 percent by dry weight of aggregate for the pretreated rubber and 6 percent for the untreated rubber. These asphalt contents were selected based on 2 percent air voids instead of the typical 4 percent, high stabilities, and acceptable VMA. The change in the selection criteria was based on anticipated field voids being higher than usual as well as the higher asphalt content will help prevent premature raveling as was seen in the Hennepin County project.

Temperature Susceptibility

The resilient moduli values over a range of temperatures are shown in Table 7.5 and Figure 7.4. All of the mixtures were similar in both their temperature susceptibility and strength. The air voids produced by reducing the compactive effort from 50 to 20 blows/side indicated that the voids in the control mixture fell within the target range of anticipated field voids (i.e., 6 to 8 percent). Both of the CRM mixtures have voids below this level; this is most likely because the optimum asphalt content was selected at 2 percent voids for the CRM mixtures instead of at 4 percent as for the control mixture. Since resilient modulus generally decreases with increasing air voids, it was anticipated that the CRM mixtures could have a lower modulus if the voids were increased to within the 6 to 8 percent range. No difference was seen between the treated or untreated crumb rubber.

Table 7.4. Mix Design Results for Babbitt Project.

Asphalt Cement Content %	Air Voids %	Marshall Stability N (lb)	Flow mm (0.01 in)	VMA	Unit Weight kN/m³ (lb/ft³)
35% Fines 65% Coarse University of Minnesota Gradations 1% Pretreated Crumb Rubber					
4.5	7.8	5,276 (1,186)	3.3 (13)	16.2	143.6
5.0	6.0	5,080 (1,142)	3.3 (13)	15.7	145.1
5.5	3.7	5,480 (1,232)	3.5 (14)	15.1	146.8
6.0	1.9	8,229 (1,850)	3.0 (12)	14.2	149.1
6.5*	1.5	7,780 (1,749)	3.5 (14)	14.8	148.8
35% Fines 65% Coarse University of Minnesota Gradations 1% Untreated Crumb Rubber					
4.5	5.9	6,570 (1477)	3.0 (12)	16.0	144.0
5.0	3.8	7,278 (1,636)	3.3 (13)	15.1	146.1
5.5	2.3	8,608 (1,935)	3.3 (13)	14.8	147.5
6.0*	1.6	9,676 (2,175)	3.0 (12)	14.7	148.2
6.5	0.2	8,701 (1956)	3.3 (13)	14.8	148.8
50% Fines 50% Coarse University of Minnesota Gradations 1% Pretreated Crumb Rubber					
5.5	3.0	9,248 (2,079)	3.3 (13)	14.4	148.8
6.0	2.2	8,447 (1,899)	3.3 (13)	14.3	149.6
6.5*	1.6	7,344 (1,651)	3.8 (15)	14.8	149.4
7.0	0.0	7,549 (1,697)	3.8 (15)	15.0	149.7
7.5	0.9	5,814 (1,307)	4.3 (17)	15.9	148.8

* selected as optimum asphalt cement content.

Table 7.5. Temperature Susceptibility.

Gradation	Rubber	Air Voids %	Resilient Modulus at Various Test Temperatures, MPa (ksi)			
			-18°C (0°F)	1°C (34°F)	25°C (77°F)	40°C (104°F)
Control	None	6.7	14,917 (2,613)	7,317 (1,061)	1,434 (203)	517 (75)
35/65	1%, Pretreated	3.1	12,717 (1,844)	7,448 (1,091)	1,537 (223)	600 (87)
35/65	1%, Untreated	4.2	11,166 (1,583)	6,248 (906)	1,628 (236)	665 (96)

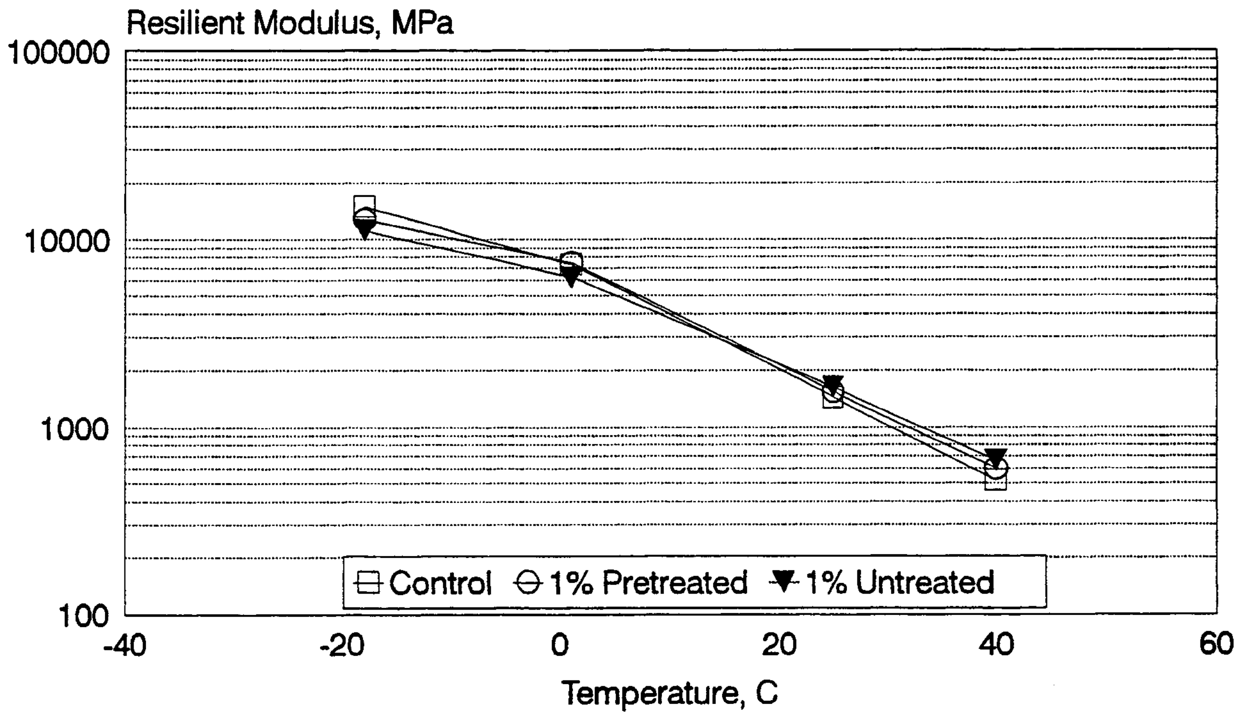


Figure 7.4. Temperature Susceptibility (Mix Design Materials).

Moisture Sensitivity

Table 7.6 shows the average test results for testing both before and after moisture conditioning. While both resilient modulus and tensile strength ratios were significantly higher for the control mixture, both modified mixtures had similar or higher absolute strengths after conditioning. However, the CRM mixtures had approximately 2 percent lower air voids; this would be expected to produce both higher strengths and lower moisture sensitivity. Therefore, it is possible that the CRM mixtures were somewhat more sensitive to moisture than the unmodified mixtures. There was little difference between either the treated or untreated CRM mixtures.

Table 7.6. Moisture Sensitivity (Mix Design Samples).

	Air Voids[1]	Resilient Modulus, 25°C (77°F) MPa (ksi)			Tensile Strength, 25°C (77°F) kPa (psi)		
		Dry	Wet	Ratio (%)	Dry	Wet	Ratio (%)
Control	6.1	1,497 (217)	1,069 (155)	71	483 (70)	469 (68)	97
35/65 1% Pretreated	4.0	2,041 (296)	1,179 (171)	58	752 (109)	476 (69)	63
35/65 1% Untreated	4.2	2,717 (394)	1,400 (203)	52	793 (119)	531 (77)	67

1: Samples compacted with 20 blows/side.

Low Temperature Behavior

Table 7.7 show the results from the low temperature indirect tensile testing. There was little difference in the tensile strengths between any of the mixtures. The corresponding horizontal strains showed a substantial increase in the ability of the modified mixtures to strain. The untreated and treated rubber increased the strain by about 35 and 42 percent, respectively.

Since the ability of the mixture to strain at cold temperatures can indicate a potential for reduced thermal cracking, either CRM mixture could potentially reduce this type of pavement distress. These results also indicate that the pretreated crumb rubber could provide a higher potential for improvement.

Table 7.7. Low Temperature Behavior.

Gradation	Air Voids[1] %	-18°C (0°F)	
		Maximum Tensile Strength kPa (psi)	Total Horizontal Strain ($\mu\epsilon \times 10^{6}$)
Control	5.9	288 (417)	438
35/65 1% Pretreated	3.2	268 (388)	749
35/65 1% Untreated	3.7	285 (413)	669

1: Samples compacted with 20 blows/side.

BABBITT, MINNESOTA FIELD TEST SECTIONS

CONSTRUCTION

All test sections were placed the week of September 8, 1993 by Glacier Paving, Inc., of Cloquet, Minnesota. This contractor had a plant equipped with an AEDCO drum mixer capable of producing about 135 metric tons/hr (150 ton/hr). The plant was located only 2.2 miles from the construction site. There were some start-up problems with the plant at the outset; plant adjustments were made and the problems solved during the production of the control mixtures and prior to the production of any of the CRM mixtures. There were also some problems and delays throughout the week due to rain.

The CRM additive was delivered to the contractor in 23 kg (50 lb.) bags. The untreated crumb rubber was packaged in poly wrap. The treated crumb rubber was supplied in paper bags, some of which had been ripped in delivery.

The CRM additive, regardless of pretreatment, was added to the hot mix by emptying the bags into the recycled asphalt pavement (RAP) hopper, timing the cycle to discharge rubber, and adjusting the speed of the RAP conveyor to match the volume of hot mix being produced. Periodic checks of the quantities of materials indicated that the desired level of 1 percent CRM additive was being achieved within $\pm$ 0.1 percent.

During the course of construction, the contractor altered the gradation from the initial 45/55 blend to between a 40/60 and 38/62 blend for the surface course; there was some concern for the coarseness of the mixture for a driving surface.

Construction of the roadway proceeded as usual; no changes were required for the CRM mixtures except that the vibration was turned off for the CRM modified sections for the base course only. During periods of rain, water beaded up on the surface of the pavement with the pretreated crumb rubber; water appeared to be absorbed by the untreated crumb rubber test sections. The influence on pavement performance by these two different types of behavior is uncertain; this phenomena should be considered when the test sections are evaluated over the next few years.

POST CONSTRUCTION

Temperature Susceptibility

Table 7.8 shows the temperature susceptibility for the materials obtained during construction. These results are compared to the values obtained for the mix design materials in Figure 7.5. This figure shows that there was little difference between the control and CRM mixtures within each group of samples (i.e., mix design, behind paver). However, the behind the paver materials showed similar moduli at the colder temperatures, somewhat higher moduli at 25°C (77°F) and slightly lower values at 40°C (104°F). This could be related to the difference in air voids between the mixtures; all of the behind the paver mixtures had approximately 2 percent lower voids than those in the mix design samples for the same compactive effort. Since the trend for lower voids in the CRM mixtures than in the control mixture was consistent for the behind the paver materials as well as the mix design material, it was expected that the in-place voids should also be lower for these mixtures.

In general, there appears to be a reasonable agreement between the design and construction mixtures. There appears to be little difference between the untreated and treated CRM mixtures at this initial stage.

Table 7.8. Temperature Susceptibility.

Gradation[1]	Air Voids %	Resilient Modulus at Various Test Temperatures, MPa (ksi)			
		-18°C (0°F)	1°C (34°F)	25°C (77°F)	40°C (104°F)
Control	4.0	18,250 (2,647)	11383 (1,048)	2,944 (427)	441 (64)
1% Untreated	1.6	18,671 (2,708)	10,025 (1,454)	2,448 (355)	325 (47)
1% Pretreated	1.4	16,816 (2,439)	8,908 (1,292)	2,413 (350)	310 (45)

1: Samples prepared at 20 blows/side compactive effort.

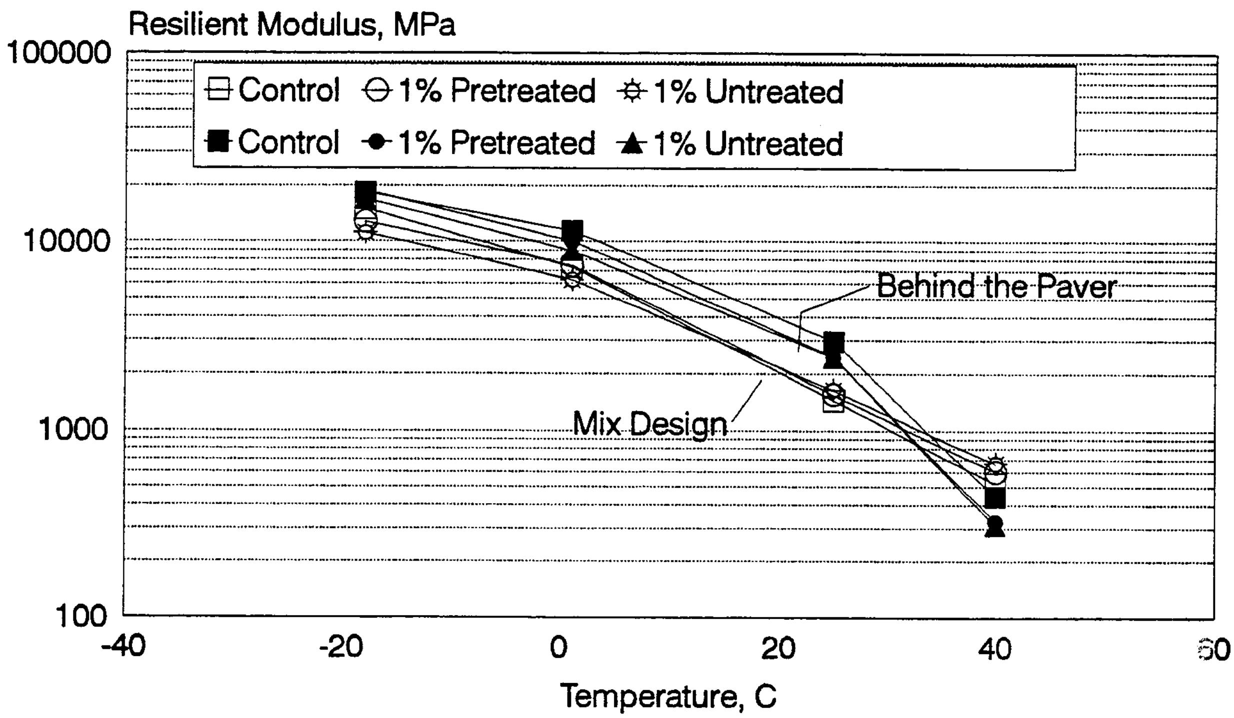


Figure 7.5. Comparison of Temperature Susceptibility for Mix Design and Behind the Paver Mixtures.

Moisture Sensitivity

Table 7.9 shows the average test results for testing both before and after moisture conditioning. While both resilient modulus and tensile strength ratios were significantly higher for the control mixture, both modified mixtures had similar or higher absolute strengths after conditioning. As mentioned previously, this is possibly a function of the difference in air voids.

A comparison of these results (Figure 7.6) to those for the mix design materials indicate a significant reduction in moisture sensitivity for the behind the paver CRM mixtures as i cated by the resilient modulus and tensile strength ratios. All of the absolute modulus values increased for the behind the paver materials. Again, these observations are most likely due to the low air voids in the behind the paver mixtures.

Table 7.9. Moisture Sensitivity (Behind the Paver Materials).

	Air Voids, %[1]	Resilient Modulus, 25°C (77°F) MPa (ksi)			Tensile Strength, 25°C (77°F) kPa (psi)		
		Dry	Wet	Ratio (%)	Dry	Wet	Ratio (%)
Control	4.0	2,944 (427)	2,276 (330)	77	897 (130)	841 (122)	94
40/60[2] 1% Untreated	1.6	2,448 (355)	2,276 (330)	93	745 (108)	807 (117)	108
40/60[2] 1% Pretreated	1.4	2,413 (350)	1,910 (277)	79	717 (104)	675 (98)	95

1: Samples compacted at 20 blows/side.
2: 40/60 field blend is equivalent to 35/65 lab blend gradation

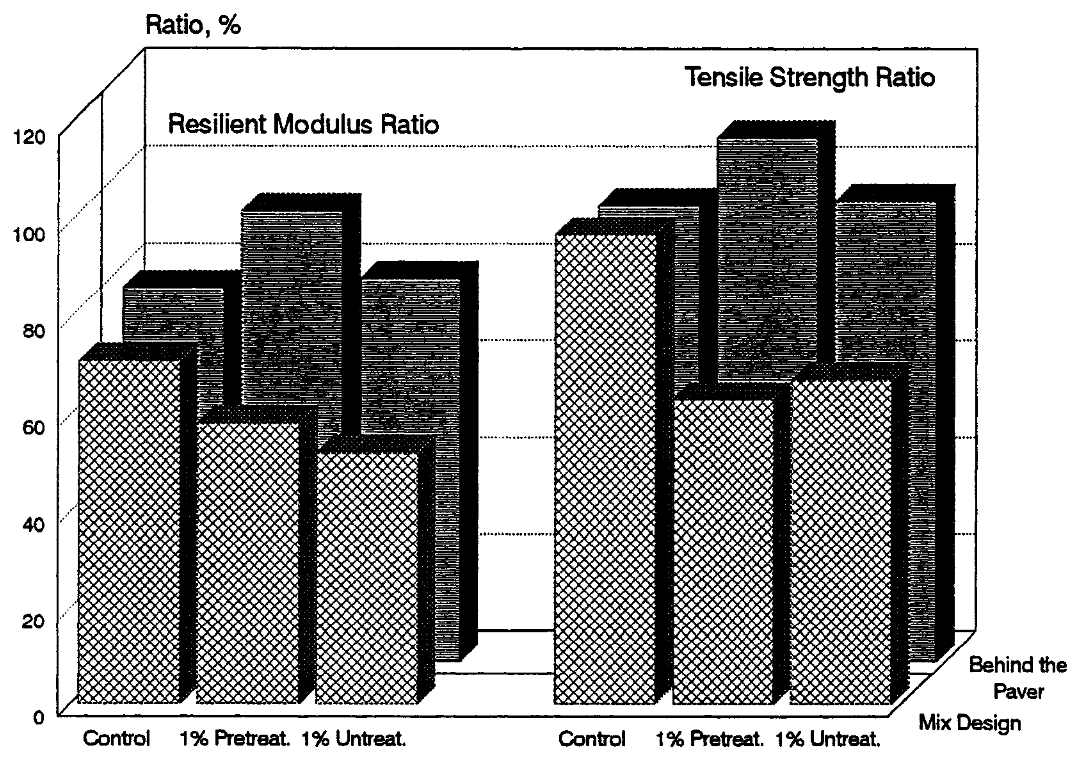


Figure 7.6. Comparison of Resilient Modulus and Tensile Strength Ratios.

Low Temperature Behavior

Table 7.10 show the results from the low temperature indirect tensile testing. The results indicated that the presence of crumb rubber in the mixture increases the ability of the mix to strain at cold temperatures. Only slight improvement was seen with the untreated crumb rubber. However the pretreated crumb rubber provided an equivalent maximum tensile strength (as compared to untreated CRM mixture) as well as increased the strain by approximately 30 percent. The pretreatment increased the strain 35 percent when compared to the unmodified mixtures. Based on these results, the pretreated crumb rubber mixture could improve the resistance of the mixture to thermal cracking.

Table 7.10. Low Temperature Behavior.

Gradation	Air Voids[1] %	-18°C (0°F)	
		Maximum Tensile Strength kPa (psi)	Total Horizontal Strain ($\mu\epsilon \times 10^6$)
Control	5.9	3,373 (542)	477
40/60[2] 1% Pretreated	3.2	3,441 (499)	645
40/60[2] 1% Untreated	3.7	3,441 (499)	504

1: Samples compacted with 20 blows/side.
2: 40/60 field blend equivalent to 35/65 lab blend gradation

Permanent Deformation Characteristics

The results from the static axial compression creep test are expressed in terms of creep modulus, which is calculated by:

$$E = \frac{\sigma_{axial}}{\epsilon_{t=60}}$$

Where:

E = creep modulus, MPa (ksi)

σ_{axial} = axial static stress, MPa (ksi)

$\epsilon_{t=60}$ = axial strain over the center 1/3 of sample after load has been applied for 60 minutes

The creep modulus, shown in Table 7.11 show the control mixture had the highest modulus, followed by the pretreated, and then the untreated CRM mixtures. These test results indicate that there is a substantial increase in the creep modulus when the crumb rubber is pretreated. As with the resilient modulus, the CRM mixtures were expected to have a greater ability to strain due to the compressible nature of the crumb rubber particles.

The implications of these results on the anticipated pavement performance are unclear at this time; the actual performance of the pavements will need to be monitored over the next several years before any conclusions can be drawn.

Table 7.11. Permanent Deformation Characteristics at Warm Temperatures.

Gradation	Creep Modulus MPa (ksi)
Control	84.5 (12.30)
40/60[1] 1% Pretreated	52.3 (7.6)
40/60[1] 1% Untreated	32.3 (4.7)

1: 40/60 field blend is equivalent to 35/65 laboratory blend gradation

CONCLUSIONS

The following conclusions can be drawn from this research:

Preconstruction Testing:

1. For the gradations used in these test sections, there was little difference in the temperature susceptibility between the control or either of the CRM mixtures. the magnitudes of resilient moduli were similar for all mixtures for any given test temperature.

2. The moisture sensitivity of the mixture increased slightly when crumb rubber was added to the mixture. However, this could also be due to the substantial change in gradations between the control and CRM mixtures.
3. The ability of the mixture to reduce thermal stresses through strain were increased substantially with the addition of crumb rubber. The largest increase was seen with the pretreated CRM mixtures.

Construction Testing:

1. The temperature susceptibility of the all mixtures were similar at any given temperature. The resilient moduli were similar to those obtained during preconstruction testing.
2. The moisture sensitivity of the behind the paver materials were similar. No increase in sensitivity was noticed for the CRM mixtures as was seen in the preconstruction testing. This is possibly due to the lower air voids in the construction samples. Little difference in pavement performance due to moisture sensitivity is anticipated for any of these mixtures.
3. As with the preconstruction testing, the pretreated CRM mixtures showed the greatest ability to dissipate stress through strain. However, there was little difference between the untreated CRM and control mixtures. This could indicate that the pretreated CRM mixture sections have potential for thermal cracking.
4. The permanent deformation characteristics showed that the control mixtures had the highest stiffness, followed by the pretreated and then untreated CRM mixtures. The implications of these results on the anticipated pavement performance are unclear without long term evaluations of the test sections.

CHAPTER EIGHT

Based on the research presented in this report, an approach for the future design and construction of crumb rubber modified asphalt concrete mixtures is suggested. These recommendations are based on using a dry process for adding coarser (i.e., approximately 10 mesh) crumb rubber particles.

EVALUATION ASPHALT-RUBBER INTERACTIONS

There should be a reasonable level of interaction between the crumb rubber and the source/grade of asphalt cement selected for the project. A suggested criteria for defining an acceptable level of interaction would be to establish a minimum viscosity of 15 Poise for a neat asphalt cement modified with 20 percent crumb rubber. This viscosity is measured with the Brookfield viscometer, a No. 3 spindle, and a rotational speed of 50 RPM's. The specific testing procedure is defined in Chapter Three. This level of viscosity appears to indicate that the solubility parameters of the selected asphalt cement and the crumb rubber are similar and compatible. The ability to obtain a sufficient level of interaction appears to be necessary regardless of whether the crumb rubber has been pretreated.

The percentage of crumb rubber used in any given project will vary widely and is ultimately dependent upon the method of modification selected (i.e., wet vs. dry process). The use of a constant percentage of crumb rubber allows for a uniform basis on which to evaluate asphalt-rubber interactions.

SELECTION OF AGGREGATE GRADATION AND OPTIMUM ASPHALT CEMENT CONTENT

The aggregate gradation should be gap-graded in order to provide the space necessary for the crumb rubber particles. The aggregate should be gapped towards the coarse side (i.e., below the maximum density line) for the best results. The target gradation used in the construction of the Babbitt, Minnesota test sections should be considered as a guideline for an acceptable gapped gradation. Gapping the gradation on the fine side can result in difficulty in compaction and premature pavement failures.

Stockpile gradations should be blended with crumb rubber gradations volumetrically; generally, 1 gram of crumb rubber occupies the same volume as 3 grams of aggregate for any given sieve size.

The optimum asphalt cement content for CRM mixtures should be based on air voids from 1.5 to 3 percent. This range, while lower than for unmodified mixtures, insures the mixture can be compacted easily and the higher film thickness should help the pavement durability. Other standard mix design parameters should be checked to insure that Marshall stability and the voids in mineral aggregate are within traditionally acceptable ranges.

CONSTRUCTION PRACTICES

When a drum plant is used to produce the asphalt concrete mixture the crumb rubber, supplied in approximately 23-kg (50-lb) polyethylene bags, can be added through the recycled asphalt pavement (RAP) hopper. Metering control of the percent of crumb rubber added should be accomplished by emptying the required number of bags into the hopper for a given quantity of hot mix moving through the plant. The same concept should be followed for using a batch plant with the exception that the crumb rubber is added to the pug mill after the introduction of the aggregate and asphalt cement.

Laydown and compaction procedures should proceed as usual except that no vibration should be used on rollers for base courses. For coarser gradations vibration can be used on upper lifts with little apparent problem. Use of vibration on the rollers when compacting a finer gradation should be used at the discretion of the field engineer.

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APPENDIX A

APPENDIX A

Standard Test Method for Determining the
VISCOSITY OF CRUMB RUBBER MODIFIED BINDERS WITH A ROTATIONAL VISCOMETER

1. Scope

1.1 This test method outlines a procedure for measuring the apparent viscosity of crumb rubber modified binders using the Brookfield HATDV-II or similar viscometer.

1.2 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 D4753 Specification for Evaluating Selecting and Specifying Balances and Scales for Use in Soil and Rock Testing.

3. Terminology

3.1 Asphalt-rubber -- AC with at least 17% rubber.

3.2 Crumb rubber modified (CRM) binder -- AC with any amount of crumb rubber.

4. Definitions

4.1 Apparent viscosity -- the ratio of shear stress to shear rate for a Newtonian or non-Newtonian liquid.

4.2 Newtonian liquid -- a liquid for which the rate of shear is proportional to the shearing stress. The constant ratio of the shearing stress to the rate of shear is the viscosity of the liquid. If the ratio is not constant, the liquid is non-Newtonian. Many liquids exhibit both Newtonian and non-Newtonian behavior, depending on the shear rate.

4.3 Viscosity -- the ratio between the applied shear stress and the rate of shear is called the coefficient of viscosity. This coefficient is a measure of the resistance to flow of the liquid. It is commonly called the viscosity. The SI unit of viscosity is the pascal second (Pa-s). The centimeter gram second (cgs) unit of viscosity is the poise (danes/cm^2) and is equivalent to 0.1 Pa-s. The centipoise (cP) is one millipascal second (mPa-s) and is used frequently as a viscosity unit.

4.4 Pseudoplastic fluid (shear thinning) -- a fluid which displays a decreasing viscosity with an increasing shear rate.

4.5 Thixotropic fluid -- a fluid which undergoes a decrease in viscosity with time, while it is subjected to constant shearing.

5. Summary of Method

5.1 400 g of asphalt cement is heated in a covered beaker to a temperature of between 150 and 180 °C (300 and 350 °F). Crumb rubber is added, and the beaker covered and returned to a 185 °C (365 °F) oven.

5.2 A spindle size for the rotational viscometer is selected in order to keep measurements within the range of the viscometer. A series of increasing and decreasing rotational speeds may be selected in order to measure shear thinning and thixotropic properties.

5.3 Prior to each viscosity measurement, the sample is mixed in order to suspend the rubber particles.

5.4 A spindle is immersed in the mixture to a specified depth and the viscosity is measured at predetermined rotational speeds.

5.5 The temperature of the sample is monitored throughout the procedure. Between measurements, the sample is kept in a constant-temperature oven to maintain a high temperature.

6. Significance and Use

6.1 This test method can be used to measure the apparent viscosity of CRM binders.

6.2 CRM binders typically contain large diameter particles that make the use of concentric cylinder or parallel plate viscometers inappropriate. For this reason, a procedure for rotational viscometers using immersible disk-type spindles is necessary.

6.3 Some asphalts may exhibit non-Newtonian behavior under the conditions of this test or during use at temperatures within the range of this method. Since non-Newtonian viscosity values are not unique material properties but reflect the behavior of the fluid and the measurement system, it should be recognized that measurements made by this method may not always predict performance under the conditions of use.

6.4 Because of these non-Newtonian flow properties, strict control must be maintained over mixing methods, temperature, and timing in order to minimize error.

6.5 Comparisons between non-Newtonian viscosity values should be made only for measurements made with similar viscometers under similar conditions of shearing stress and shear history.

7. Apparatus

7.1 Ovens, one capable of maintaining a temperature of 185 ± 5 °C (365 ± 9 °F), and a second capable of maintaining 135 ± 5 °C (275 ± 9 °F).

7.2 Viscometer, Brookfield HATDV-II or similar, with various spindle sizes and a minimum of 4 RPM settings (e.g. 10, 20, 50, 100 RPM).

7.3 Thermometer, glass, in the range from 30 to 200 °C (100 to 400 °F) and graduated in 0.5 °C (1 °F) subdivisions conforming to the requirements for ASTM Thermometer 16C (16F) given in Specification E1.

7.4 Ring Stand, with clamp, for mounting thermometer.

7.5 Beakers, glass, 600 ml pyrex.

7.6 Spatula, stainless steel with wooden handle, in a size appropriate for mixing in a 600 ml beaker (10 X 2 cm blade).

7.7 Laboratory Balance, minimum of 750 g capacity, sensitive to 0.1 g. The balance shall conform to Specification D4753 as a class GP2 balance.

7.8 Stopwatch, accurate to 0.1 second.

7.9 Stainless Steel Canister, approximately the same height as and 20 to 50 mm larger in diameter than the beaker, lined with a heat-resistant insulating material such as fiberglass insulation or a large pot holder.

8. Preparation of Samples

8.1 Heat the sample with care in 135 °C (275 °F) oven, stirring when possible to prevent local overheating, until it has become sufficiently fluid to pour.

8.2 Label and weigh a 600 ml beaker for each sample to be tested. Designate this mass as **A**.

8.3 Pour 350 ± 5 g of asphalt cement into each beaker and weigh. Designate this mass as **B**.

8.4 Immediately cover the beaker with aluminum foil and place in a 185 ± 5 °C (365 ± 9 °F) oven. Heat for 45 minutes or until AC temperature is 185 ± 5°C (365 ± 9 °F).

8.5 Mixing

8.5.1 Crumb rubber may need to be oven dried before mixing. The moisture content of crumb rubber must be very low when it is mixed with hot asphalt. Any water in the rubber will vaporize when it contacts the asphalt and cause a rapid volume expansion due to foaming.

8.5.2 Select a percentage of crumb rubber to be added to each beaker. Weigh out crumb rubber to be added to each beaker. Designate this mass as **C**.

8.5.3 Remove one beaker from oven, add crumb rubber and stir 50 times at approximately 2 rotations per second. Immediately cover and return beaker to oven. Beaker shall not be out of oven for more than 2 minutes.

8.5.4 Record the time of mixing.

8.5.5 Repeat procedure for remaining beakers at 10 minute intervals.

8.6 A spindle shall be selected such that the measurements range between 10 and 70 percent of the viscometer's maximum torque for each of the rotational speeds used. If different percentages of rubber are to be tested, one spindle size may not be sufficient for all samples.

9. Viscosity measurements

9.1 Remove one beaker from oven and place it in an insulated stainless steel canister.

9.2 Lower the thermometer into the beaker with the bulb at the approximate depth of the rotating disk, and approximately 10 mm from side of beaker, and clamp into place.

9.3 Stir the sample 50 times at approximately 2 rotations per second. Be careful not to bump the thermometer.

9.4 Bring the spindle to the test temperature by immersing the spindle in the sample to the depth specified in the operator's manual set at maximum rotational speed and run for 30 seconds. Stop the spindle and stir the sample 10 times without removing the spindle.

9.5 Verify that the sample temperature is within ± 5 °C (± 9 °F) of the desired temperature.

9.6 Reset speed to 10 RPM. Start the equipment and stopwatch at the same time. Take a viscosity reading at 10 seconds. Immediately increase speed to 20 RPM's and take another reading after 10 seconds. Repeat until viscosity for 10, 20, 50, and 100 RPM's have been tested

9.7 Cover sample with aluminum foil and return to 185 ± 5 °C (365 ± 9 °F) oven immediately after measuring.

10. Calculations

10.1 Calculate percent of rubber used:

$$CR = A/(C-B)$$

Where:
A = mass of rubber, g.
B = mass of beaker, g.
C = mass of beaker and asphalt cement, g.

10.2 If the viscometer used does not give a direct viscosity reading, the viscosity can be calculated by multiplying the scale deflection **a** on the torque dial (in scale units of the 0-100 scale) by the spindle constant given by the manufacturer.

10.3 If different spindle sizes are used, shear rate values should be used for comparison. Calculate shear rates as follows:

10.3.1 Record the scale deflection **a**, and the rotational speed **N** (in rpm).

10.3.2 Calculate the average shear stress **t** on each spindle (in Pa) as follows:

$$t = k_{at}a$$

Where: a = scale deflection on the torque dial

k_{at} = spindle constant (see Table 1).

10.3.3 Plot **t** vs. **N** on log-log paper, with **t** on the y-axis.

10.3.4 If the relationship is sufficiently linear, draw a straight line through the points and calculate the flow index of the fluid, **n**, which is the slope of the line:

$$n = [\log(t_2)-\log(t_1)]/[\log(N_2)-\log(N_1)].$$

Where: (N_1,t_1) = rotational speed and shear stress coordinates of a point on the line near the left side of the graph.

(N_2,t_2) = rotational speed and shear stress coordinates of a point on the line near the right side of the graph.

10.3.5 Calculate the shear rates **v** (in s^{-1}) as follows:

$$v = k_{Ny}(n)N$$

Where: n = flow index.

N = rotational speed.

k_{Ny} = conversion factor (see Table 1).

10.3.6 If the relationship is not linear, draw a smooth curve through the points. The apparent flow index $\mathbf{n}^*$ at a given rotational speed is the slope of the tangent at the corresponding point on the curve. Draw a tangent at each rotational speed and calculate the apparent flow index $\mathbf{n}^*$ for each line using the equation from 10.3.4.

10.3.7 Calculate the shear rates v as follows:

$$v = k_{Ny}(n^*)N$$

Where: n^* = apparent flow index.

N = rotational speed.

k_{Ny} = conversion factor (see Table 1).

Table 1. Conversion factors for the spindles of the Brookfield R.V.T. viscometer (under standard measuring conditions)

(Reproduced from Mitschka, P., "Simple conversion of Brookfield R.V.T. readings into viscosity functions," Rheological Acta, Vol. 21, No. 2, 1982, p. 208.

Spindle number		1	2	3	4	5	6	7
k_{at}		0.035	0.119	0.279	0.539	1.05	2.35	8.4
	n = 0.1	1.728	1.431	1.457	1.492	1.544	1.366	1.936
	0.2	0.967	0.875	0.882	0.892	0.907	0.851	1.007
	0.3	0.705	0.656	0.656	0.658	0.663	0.629	0.681
	0.4	0.576	0.535	0.530	0.529	0.528	0.503	0.515
k_{Ny}	0.5	0.499	0.458	0.449	0.445	0.442	0.421	0.413
	0.6	0.449	0.404	0.392	0.387	0.382	0.363	0.346
	0.7	0.414	0.365	0.350	0.343	0.338	0.320	0.297
	0.8	0.387	0.334	0.317	0.310	0.304	0.286	0.261
	0.9	0.367	0.310	0.291	0.283	0.276	0.260	0.232
	1.0	0.351	0.291	0.270	0.262	0.254	0.238	0.209

11. Report

11.1 Report test temperature (°C).

11.2 Report viscosity (Poise).

11.3 Report shear rate (s^{-1}).

11.4 Report rubber content (%).

APPENDIX B

APPENDIX B

The cone test for surface moisture of aggregate (ASTM C128) was used to determine the optimum tall oil content to treat the crumb rubber. The general concept and principle to determine the optimum surface moisture for fine aggregate was applied to find the optimum tall oil content in the crumb rubber. The differences are in the materials and the mix temperature. The temperature of the crumb rubber treatment was 135 ± 5 °C (275 ± 10 °F).

The procedure for the crumb rubber treatment was as follows:

1. Put the required amount of tall oil in a 30 x 60 cm (1 x 2 ft.) rectangular stainless steel pan and put the pan in an oven for 10 minutes at 135 °C (275 °F).
2. Put the required amount of crumb rubber in another pan and put them in the oven for 5 minutes along with a steel spoon.
3. Spread the heated crumb rubber evenly on the tall oil and mix them gently with a heated spoon.
4. If the temperature of the crumb rubber drops below the mixing temperature range put it back in the oven for 5 minutes. Then remove and mix it gently.
5. Repeat step 4 until the crumb rubber particles are thoroughly coated (until the tall oil is not seen on the surface of pan).

5 Put the treated crumb rubber in the vinyl bag and store at the room temperature.

The following equipment is needed to determine the optimum tall oil content for the treatment of crumb rubber:

<u>Mold</u> : A metal mold in the form of a cone with dimensions as follows: 40 ± 3 mm inside diameter at the top, 90 ± 3 mm inside diameter at the bottom, and 75 ± 3 mm

in height, with the metal having a minimum thickness of 0.8 mm.

Tamper : A metal tamper weighing 340 ± 15 grams and having a flat circular tamping face 25 ± 3 mm in diameter.

The procedure for this test was as follows.

1. Hold the mold firmly on a smooth nonabsorbent surface with the large diameter down.
2. Place a portion of the partially treated crumb rubber loosely in the mold by filling it to overflowing and heaping additional material above the top of the mold by holding it with the cupped fingers of the hand holding the mold.
3. Lightly tamp the treated crumb rubber into the mold with 25 light drops of the tamper. Each drop should start about 5 mm (0.2 in.) above the top surface of the treated crumb rubber. Permit th[illegible]per to fall freely under gravitational attraction on each drop. Adjust the starting height to the new surface elevation after each drop and distribute the drops over the surface.
4. Remove the loose treated crumb rubber from the base and lift the mold vertically. When the treated crumb rubber slumps slightly it indicates that it has reached an optimum tall oil content.

APPENDIX C

APPENDIX C

The following steps were used in the mixing procedure of the CRM asphalt concrete:

1. Weigh the required amounts of aggregates and treated crumb rubber.
2. The crumb rubber is to remain at room temperature until step 6.
3. Heat the aggregates to 135 ± 5 °C (275 ± 10 °F) for 12 hours.
4. Heat the asphalt cement and mixing bowl to 135 ± 5 °C (275 ± 10 °F) for 4 hours.
5. Put the heated aggregates and add the target amount of asphalt cement into the mixing bowl.
6. Place the mixing bowl on the automatic mixer and mix thoroughly.
7. During the mixing gradually add the treated crumb rubber.
8. Continue mixing until all particles are thoroughly coated (about 3 minutes).

The compaction procedure for Marshall samples was :

1. Heat the molds and Marshall hammer to 135 ± 5 °C (275 ± 10 °F) for 2 hours.
2. Place a 4-in. diameter paper disc on the bottom of the mold.
3. Put 1100 grams of asphalt concrete mixture (1050 grams for asphalt-rubber mixtures) and tamp it 25 times with a spatula (10 times in the middle, 15 times around the edge).
4. Place a 4-in. diameter paper disc on the top of the mixture.
5. Place the mold in the Marshall compactor and compact the mixture for the required number of blows on one side.
6. Compact the other side for the required number of blows.
7. Let the sample rest for 1 hour at room temperature.
8. Remove the sample from the mold using a hydraulic extruder and write the sample number on the bottom of the sample.

9. Measure and calculate the height and bulk specific gravity of the sample and store it at test temperature.

APPENDIX D

APPENDIX D

The complete mix design results for all gradations are shown below.

Control Gradation (AC 120/150; 0 % Rubber)

% A.C[1]	BSG[2]	MSG[3]	Stability[4]	Flow[5]	% Void[6]	VMA[7]
3.5	2.351	2.553	3200	11	7.9	14.3
4.0	2.373	2.529	3200	9	6.2	13.9
4.5	2.377	2.499	2800	10	4.9	14.8
5.0	2.415	2.490	3000	10	3.0	13.2
5.5	2.428	2.451	3000	12	1.0	13.2

[1] Percent Asphalt Cement [2] Bulk Specific Gravity [3] Maximum Specific Gravity
[4] Unit in pounds (1 lb = 4.4482 Newtons) [5] Unit in 0.01 in. (1 in. = 25.4 mm)
[6] Percent Air Void Contents [7] Voids in Mineral Aggregate

Control Gradation (AC 120/150; 3 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.152	2.344	1492	13	3.8	14.6
6.5	2.235	2.350	1272	15	4.9	15.8
7.0	2.244	2.348	1253	17	4.4	15.9
7.5	2.275	2.312	1197	16	1.8	15.2
8.0	2.286	2.310	1207	17	1.1	15.3

Control Gradation (AC 120/150; 3 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
4.0	2.152	2.442	1378	21	11.9	16.8
4.5	2.190	2.442	1578	18	10.3	15.8
5.0	2.193	2.406	1600	17	8.9	16.1
5.5	2.171	2.388	797	18	9.1	17.4
6.0	2.190	2.377	674	20	7.9	17.1

RESULTS OF MIX DESIGN

Control Gradation (AC 120/150; 5 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.5	2.128	2.263	931	19	5.9	17.5
7.0	2.138	2.260	845	22	5.4	17.6
7.5	2.096	2.240	722	20	6.4	19.7
8.0	2.077	2.204	711	22	5.8	20.8

Control Gradation (AC 120/150; 5 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
4.0	2.042	2.399	659	20	14.9	18.7
4.5	2.043	2.370	759	21	13.8	19.1
5.0	2.042	2.364	831	18	13.6	19.6
5.5	2.026	2.372	845	21	14.6	20.6
6.0	2.036	2.349	866	24	13.3	20[illegible]

Gradation A (AC 120/150; 0 % Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
3.5	2.399	2.547	3908	5	5.8	10.8
4.0	2.424	2.519	2678	6	3.8	10.4
4.5	2.450	2.504	3213	7	2.1	9.9
5.0	2.464	2.484	3163	10	0.8	9.9
5.5	2.470	2.470	2354	11	0.0	10.1

Gradation A (AC 120/150; 3 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
5.0	2.211	2.403	1439	18	8.0	15.4
5.5	2.252	2.417	1753	14	6.8	14.3
6.0	2.265	2.400	1833	13	5.6	14.3
6.5	2.288	2.372	1692	15	3.6	13.9
7.0	2.270	2.338	1217	16	2.9	15.0

Gradation A (AC 120/150; 3 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
5.5	2.216	2.409	1682	14	8.0	15.7
6.0	2.285	2.377	2111	13	3.9	13.5
6.5	2.276	2.357	1741	16	3.4	14.3
7.0	2.275	2.332	1416	20	2.4	14.8
7.5	2.287	2.316	1260	19	1.2	14.8

Gradation A (AC 120/150; 5 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.110	2.318	1023	16	8.9	17.8
6.5	2.084	2.314	996	19	9.9	19.2
7.0	2.082	2.322	872	25	10.3	19.8
7.5	2.186	2.276	1123	18	3.9	16.2
8.0	2.152	2.261	1008	21	4.8	18.0

Gradation A (AC 120/150; 5 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.054	2.338	902	21	12.2	20.0
6.5	2.085	2.324	943	21	10.3	19.2
7.0	2.118	2.310	868	23	8.3	18.4
7.5	2.182	2.296	1180	20	5.0	16.4
7.0	2.179	2.287	1025	23	4.6	16.9

Gradation B (AC 120/150; 0 % Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
3.5	2.358	2.542	2789	9	7.3	12.4
4.0	2.367	2.521	2329	8	6.1	12.5
4.5	2.382	2.517	2402	7	5.4	12.5
5.0	2.430	2.481	2412	7	2.1	11.1
5.5	2.441	2.459	2435	7	0.8	11.2

RESULTS OF MIX DESIGN

Gradation B (AC 120/150; 3 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.165	2.382	912	16	9.1	18.1
6.5	2.180	2.352	895	16	7.3	18.0
7.0	2.196	2.336	830	17	6.0	17.8
7.5	2.262	2.318	1209	14	2.4	15.8
8.0	2.251	2.310	1029	17	2.5	16.6

Gradation B (AC 120/150; 3 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
5.5	2.233	2.408	1307	15	7.3	15.1
6.0	2.209	2.396	1113	16	7.8	16.4
6.5	2.200	2.379	1159	15	7.5	17.2
7.0	2.220	2.348	1188	16	5.5	16.9
7.5	2.245	2.315	1069	15	3.0	16.4

Gradation (AC 120/150; 5 % Untreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.124	2.294	1054	20	7.4	17.3
6.5	2.088	2.301	872	20	9.3	19.2
7.0	2.085	2.292	772	23	9.0	19.7
7.5	2.082	2.302	738	24	9.6	20.2
8.0	2.158	2.258	1056	20	4.4	17.7

Gradation (AC 120/150; 5 % Pretreated Rubber)

% A.C	BSG	MSG	Stability	Flow	% Void	VMA
6.0	2.089	2.299	879	20	9.1	18.7
6.5	2.074	2.285	816	21	9.2	19.7
7.0	2.091	2.271	839	22	7.9	19.4
7.5	2.151	2.258	956	20	4.8	17.6
8.0	2.191	2.245	1056	18	2.4	16.5

APPENDIX E

APPENDIX E

INDIRECT TENSILE TEST

The indirect tensile test is a form of tensile strength test used for stabilized materials.In this test, diametrically opposed line loads are applied to a cylindrical specimen (Figure E.1). The theory of the indirect tensile test is usually developed from Frocht's (A.1) equations for point loads P applied at the ends of the diameter for an idealized elastic material. The distributions of stresses calculated from Frocht's equations are shown in Figure E.2 for the vertical diameter (along the loading axis). Along the vertical diameter, the horizontal stress σ_x which is constant, the vertical stress σ_y, and the shear stress τ_{xy} are given by expressions (Tensile stresses are considered to be positive):

$$\sigma_x = \frac{2P}{\pi t D} = \text{constant} \quad \text{(E.1)}$$

$$\sigma_y = -\frac{2P}{\pi t}\left[\frac{2}{d-2y} + \frac{2}{d+2y} - \frac{1}{d}\right] \quad \text{(E.2)}$$

$$\tau_{xy} = 0 \quad \text{(E.3)}$$

where:

P = applied load

t = thickness of the specimen

d = diameter of the specimen

x, y = coordinate values from center of specimen

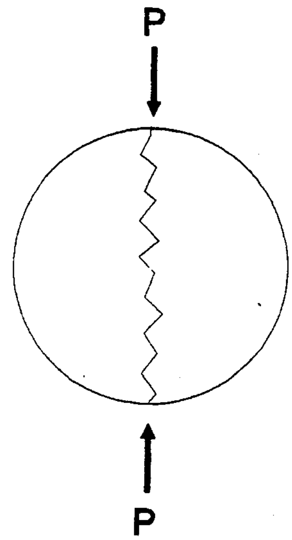

Figure E.1. Indirect Tensile Test with Point Line Loading.

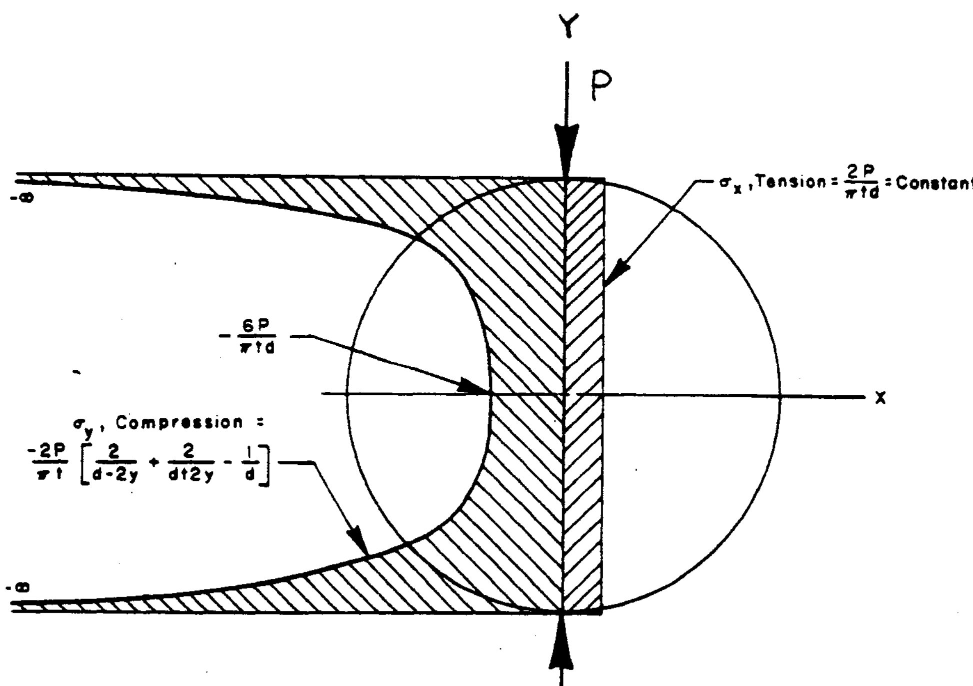

Figure E.2. Stress Distributions along T-Axis for Indirect Tensile Test (A.1).

Hondros (2) has analyzed the stress distribution in this test for the case of a thin disc loaded by a uniform pressure, radially applied over a short strip of the circumference at each end of a diameter (Figure E.3). The expressions of the stress distributions along the loaded diameter are given by follows:

$$\sigma_{\theta y} = +\frac{2p}{\pi}\left[\frac{(1-r^2/R^2)\sin 2\alpha}{1-2r^2/R^2\cos 2\alpha + r^4/R^4} - \tan^{-1}\left(\frac{1+r^2/R^2}{1-r^2/R^2}\right)\tan\alpha\right] \qquad \text{(E.4)}$$

$$\sigma_{xy} = -\frac{2p}{\pi}\left[\frac{(1-r^2/R^2)\sin 2\alpha}{1-2r^2/R^2\cos 2\alpha + r^4/R^4} + \tan^{-1}\left(\frac{1+r^2/R^2}{1-r^2/R^2}\right)\tan\alpha\right] \qquad \text{(E.5)}$$

where:

$\sigma_{\theta y}$ = tangential normal stress at a point on the loaded axis

σ_{ry} = radial normal stress at a point on the loaded axis

P = applied load

p = load per unit area of strip (p = P/at)

a = projected width of the loaded section of the rim

t = thickness of the disc

2α = angle subtended at the center of the disc by the loaded section of the rim

r = radial distance of a point from the center of the disc

R = radius of the disc

Fairhurst (3) showed the variation of stress, $\sigma_{\theta y}$, and σ_{ry} along the loaded diameter for the case where $\alpha = \tan^{-1}(1/12)$ (Figure E.4). At the center, eq.(E.4) is yielding:

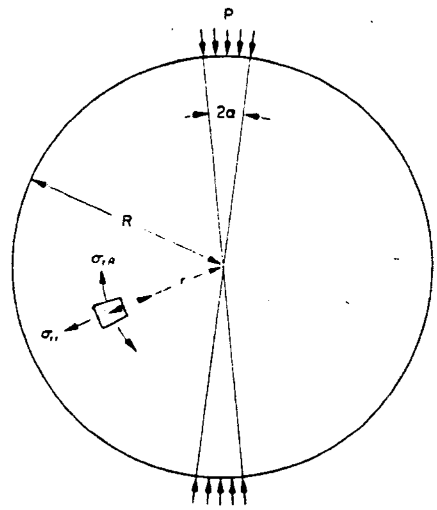

Figure E.3. Indirect Tensile Test with Strip Line Loading (A.3).

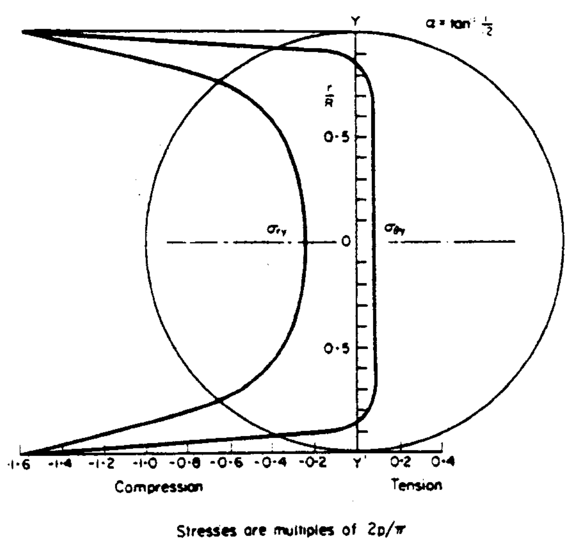

Figure E.4. Stress Distributions along Y-Axis for Indirect Tensile Test (A.3).

$$\sigma_{\theta y} = \frac{2p}{\pi}(\sin 2\alpha - \alpha) \approx \frac{2p\alpha}{\pi} \qquad \text{(E.6)}$$

Substituting P/dt = pα into eq. (E.6), where d is a diameter of the disc,

$$\sigma_{\theta y} = \frac{2P}{\pi t d} \qquad \text{(E.7)}$$

It is seen that eq.(E.7) is same as the solution of Frocht (eq.E.1).

Under the loading condition of the indirect tensile test, the specimen would be expected to fail near the load points due to compressive stresses and not in the center portion of the specimen due to tensile stresses (Figure E.2 or eqs.(E.1) and (E.2)). It has been shown, however, that these compression stresses are greatly reduced by distributing the load through a loading strip. In addition, the horizontal tensile stress along the vertical diameter change from tension to compression near the points of loading application (Figure E.4). The failure usually occurs by splitting along the load plane and the tensile strength of the specimen, σ_t, can be calculated with eqs. (E.1) and (E.7) or:

$$\sigma_t = \frac{2P}{\pi t d} \qquad \text{(E.8)}$$

DIAMETRAL RESILIENT MODULUS TEST

The resilient modulus M_r is a ratio of applied stress to recoverable resultant strain. It is close to conditions which prevail in the field since a loading pulse is followed by a rest period and the loading time and rest period can be varied to represent a different vehicle speed and traffic intensity.

The diametral resilient modulus test is basically a repetitive load test using the stress distribution principles of the indirect tensile test previously discussed (Figure E.1). The resilient modulus is a form of an elastic modulus which is solved with Frocht's equations for an idealized elastic material subjected to diametrically opposed point loads. The distributions of stresses calculated from Frocht's equations are shown in Figure E.5 for the horizontal diameter (perpendicular to the loading axis). Along the horizontal diameter, the horizontal stress σ_x, the vertical stress σ_y, and the shear stress τ_{xy} are expressed as follows:

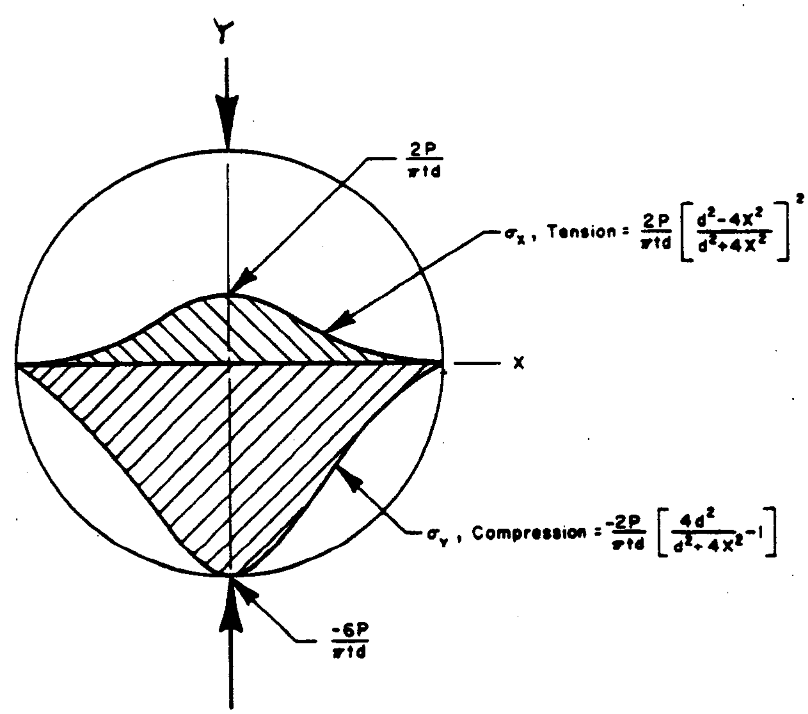

Figure E.5. Stress Distributions along X-Axis for Indirect Tensile Test (A.1).

$$\sigma_x = +\frac{2P}{\pi td}\left[\frac{d^2-4x^2}{d^2+4x^2}\right]^2 \tag{E.9}$$

$$\sigma_y = -\frac{2P}{\pi td}\left[\frac{4d^2}{d^2+4x^2}-1\right] \tag{E.10}$$

$$\tau_{xy} = 0 \tag{E.11}$$

Assuming that plane stress conditions ($\sigma_z = 0$), and using the Hooke' law, the resultant (horizontal) strain ϵ_x can be expressed as:

$$\epsilon_x = \frac{1}{E}[\sigma_x - \nu\sigma_y] \tag{E.12}$$

where:

E = elastic modulus of the material

ν = Poisson's ratio

Substitution of eqs. (E.10) and (E.11) into eq.(E.12) results in:

The displacement across the horizontal diameter (y=0) can be calculated by integrating

$$\epsilon_x = \frac{2P}{E\pi td}\left[\frac{d^4(1+5\nu)-8x^2d^2(1-3\nu)+16x^4(1+\nu)}{(d^2+4x^2)^2}\right] \tag{E.13}$$

eq.(E.13) from x = -d/2 to x = +d/2. This results in the horizontal displacement u_x being equal to:

$$u_x = \frac{P}{Et}[\frac{4}{\pi} + \nu - 1] \tag{E.14}$$

Knowing the applied load P and the horizontal displacement u_x, the elastic modulus E can be calculated as:

$$E = \frac{P(\nu + 0.2734)}{tu_x} \tag{E.15}$$

and it can be used as a resilient modulus M_r since the resilient modulus a form of the elastic modulus in this special case.

APPENDIX

A.1. Frocht, M. M., "Photoelasticity 2," Wiley, New York, 1957.

A.2. Hondros, G., "The Evaluation of Poisson's Ratio and The Modulus of Materials of A Low Tensile Resistance by The Brazilian (Indirect Tensile) Test With Particular Reference on Concrete," Aust. J. Appl. Sci., vol. 10, No. 3., pp 243-268, 1959.

A.3. Fairhurst, C., "On The Validity of The 'Brazilian' Test for Brittle Materials," Int. J. Rock Mining Sci. vol. 1, pp 535-546, 1964.

APPENDIX F

APPENDIX F

INDIRECT TENSILE TEST

AC 85/100

Mixture Type	Temp[1]. (°C)	St[2] (kPa)			H.Strain[3] ($x10^{-6}$)		
Control	-18	4006	4105	4171	189	166	151
	1	3258	3179	2965	311	760	692
PA[4] 3%	-18	2103	2689	2182	361	368	276
	1	1520	1362	1497	777	976	961
PA 5%	-18	1586	1898	1580	632	542	676
	1	1072	1455	1109	1329	1148	1316
IN[5] 3%	-18	2127	2199	2175	505	312	317
	1	1562	1844	1508	702	935	968
IN 5%	-18	2122	2079	1889	512	436	396
	1	1156	1180	1235	1243	1135	1361

[1] Temperature; [2] Tensile Strength; [3] Horizontal Strain; [4] Passenger Tire; [5] Industrial Tire

AC 120/150

Mixture Type	Temp. (°C)	St (kPa)			H. Strain ($x10^{-6}$)		
Control	-18	4858	4814	4885	206	217	198
	1	2433	2536	2506	1370	1493	1321
PA 3%	-18	1668	1786	1544	382	337	364
	1	1156	1182	1071	1246	1142	1160
PA 5%	-18	1368	1513	1322	771	719	752
	1	867	875	909	1405	1738	1598
IN 3%	-18	2101	2035	1878	401	392	388
	1	1530	1511	1474	1348	1242	1308
IN 5%	-18	1602	1494	1295	625	671	593
	1	920	979	1040	1596	1574	1612

RESILIENT MODULUS TEST

Control Mixture (AC 85/100)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	5216	5986	6894	6125
	4999	6262	7369	
1	3891	3898	3556	3715
	3636	3611	3735	
25	3125	2802	3101	2940
	2841	2598	3161	
40	1331	1141	1508	1381
	1473	1336	1493	

3% Passenger Tire Rubber Mixture (AC 85/100)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	4373	4649	5102	4773
	4779	4932	4785	
1	2928	3299	3144	3073
	2942	2992	3121	
25	1930	2072	2076	2055
	2123	2062	2057	
40	811	814	864	844
	846	872	855	

5% Passenger Tire Rubber Mixture (AC 85/100)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	3556	3786	4134	3831
	3664	3730	4096	
1	2534	2765	2709	2699
	2630	2612	2930	
25	1250	1327	1355	1333
	1345	1420	1299	
40	540	586	572	582
	594	579	622	

3% Industrial Tire Rubber Mixture (AC 85/100)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	4493	4689	4605	4549
	4388	4435	4705	
1	2302	2525	2475	2471
	2449	2650	2437	
25	2140	2000	1691	1890
	1946	1894	1670	
40	652	712	778	728
	679	715	832	

5% Industrial Tire Rubber Mixture (AC 85/100)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	3582	3478	3446	3584
	3734	3468	3790	
1	1916	1931	1871	1907
	1846	1992	1877	
25	1126	968	1032	1047
	1126	1000	1029	
40	431	388	406	433
	481	447	446	

Control Mixture (AC 120/150)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	7119	6758	6797	6893
	7074	6804	6784	
1	5055	5646	5434	5366
	5459	5362	5240	
25	1948	2622	-	2350
	2332	2494	-	
40	1313	1573	1464	1355
	1170	1277	1335	

3% Passenger Tire Rubber Mixture (AC 120/150)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	5193	5285	-	5321
	5318	5498	-	
1	3638	4296	3900	3875
	3708	3816	3884	
25	1540	1840	1791	1731
	1590	1780	1843	
40	797	804	991	880
	815	860	1005	

5% Passenger Tire Rubber Mixture (AC 120/150)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	5520	4940	-	5118
	5124	4873	-	
1	3079	3283	2940	3052
	3201	3128	2667	
25	1154	1300	861	1130
	1195	1294	967	
40	389	-	-	514
	638	-	-	

3% Industrial Tire Rubber Mixture (AC 120/150)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	4435	4517	4318	4482
	4631	4674	4296	
1	2511	2388	2444	2463
	2395	2617	2412	
25	1341	1344	1118	1273
	1335	1319	1173	
40	499	445	422	461
	511	482	401	

5% Industrial Tire Rubber Mixture (AC 120/150)

Temp (°C)	M_R (MPa)			Average (MPa)
-18	3581	3101	3517	3392
	3474	3270	3391	
1	1794	1887	1817	1818
	1732	1867	1800	
25	792	880	819	832
	799	868	830	
40	274	306	256	291
	284	327	294	